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Cost Comparisons of Treatment and Disposal Alternatives for Hazardous Wastes. Volume I

SCS Engineers, Inc.
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COST COMPARISONS OF TREATMENT AND DISPOSAL ALTERNATIVES FOR HAZARDOUS WASTES

Volume I

by

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Contract No. 68-03-2754

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16. ABSTRACT

Unit costs are estimated for 16 treatment and 5 disposal techniques applicable to hazardous wastes from the organic chemicals, inorganic chemicals, and electroplating and metal finishing industries. Each technology was evaluated by unit processes or modules, and computer-linked models developed for calculating capital and operating costs at the unit process level. Costs were aggregated at the technology level including applicable indirect costs and maintenance costs. Data files were designed to indicate economies of scale for 5 levels of throughput. Life cycle average unit costs are presented in both tabular and graphic form.

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to treat and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

The purpose of this study is to enhance the understanding of hazardous waste treatment and disposal economies. The multitude of applicable and emerging technologies in this area must be described and priced to allow waste managers to make informed decisions. This report provides the user community with the necessary cost data, analytical and comparative techniques, and recommendations for cost-effective management options based on the type of waste and scale of operation.

Francis T. Mayo,
Director
Municipal Environmental Research
Laboratory

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ABSTRACT

This project is intended to standardize, update, and evaluate cost and technological data pertaining to treatment/disposal options for hazardous wastes from the organic chemicals, inorganic chemicals, and the electroplating and metal finishing industries. Sixteen treatment and five disposal technologies were selected for study based on their applicability within the industrial categories, the availability of cost and performance data, and their overall effectiveness in reducing or eliminating the hazardous waste constituents.

Each technology was assessed in terms of its unit processes or modules, and computer-linked models were developed for calculating capital and operation/maintenance costs at the unit process level. Costs were then aggregated at the technology level together with all applicable indirect capital and operation/maintenance costs. Cost data were entered in the models at the unit cost or cost component level (e.g., dollars/yd^3 of concrete), and the data files were designed to accommodate economies of scale.

Technology costs derived from the analyses (provided in both tabular and graph format) are presented for site preparation, structures, mechanical equipment, electrical equipment, land and other capital. Operation/maintenance cost categories include three classes of labor, energy, maintenance, and chemicals. Final cost comparisons among treatment/disposal technologies applicable to similar waste streams are made on a life cycle average cost basis.

Risks associated with the existence and operation of each technology are also assessed. Each technology is rated and compared in terms of susceptibility to catastrophic events, unexpected downtime, and adverse environmental impacts.

This report was submitted in fulfillment of Contract No. 68-03-2754 by SCS Engineers under the sponsorship of the U.S. Environmental Protection Agency. It covers the period September 25, 1978, to August 25, 1979, and work was completed as of October 25, 1979.

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METRIC CONVERSION FACTORS

ABBREVIATION	DEFINITION	METRIC EQUIVALENT
EA	Each	N.A.
SF	square feet	x 0.0929 = square meters
LF	linear feet	x 0.3048 = linear meters
FT	feet	x 0.3048 = meters
DIA"	diameter (in inches)	x 2.54 = centimeters
DIA'	diameter (in feet)	x 0.3048 = meters
HP	horsepower-hour	x = 0.7457 KWH
LBS	pounds	x 0.454 = kilograms
GAL	gallons	x 3.785 = liters
GPM	gallons per minute	x 3.785 = liters per minute
GPD	gallons per day	x 3.785 = liters per day
CF	cubic feet	x 0.028 = cubic meters
BTU	British Thermal Unit	x $1.06x10^{10}$ = ergs
LBS/HR	pounds per hour	x 0.454 = kilograms per hour
TONS/HR	tons per hour	x 0.907 = metrictons per hour
IN	inch	x 2.54 = centimeter
CY	cubic yard	x 0.765 = cubic meter
BDFT	board feet	x 0.3048 = board meters
KWH	kilowatt-hour	N.A.
^{o}C	degrees centigrade	x 9/5+32 = degrees fahrenheit
PPM	parts per million (miligrams per liter)	N.A.
PSIG	pounds per square inch	x 703.1 = kilograms per sq. meter
BOD	biological oxygen demand	N.A.
TSS	total suspended solids	N.A.

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Finally, the authors wish to acknowledge the assistance and cooperation demonstrated by the numerous equipment manufacturers, retailers, and hazardous waste managers contacted during this study.

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SECTION 1

INTRODUCTION

OBJECTIVES

The primary purpose of this study is to provide guidance and tools for hazardous waste managers in selection of cost-effective treatment and disposal schemes. This information may be used by engineers in the preliminary design of treatment/disposal processes and by decision makers in determining whether such systems are appropriate to specific industrial or municipal waste streams. It is intended that the report serve as a guideline for 1) making cost estimates for designated processes, and 2) making cost-effectiveness comparisons among two or more process options. As described in Section 5 (Procedure for Cost Analysis), there is sufficient flexibility within the cost and technical models so the user can accommodate special project or regional needs.

Specific project objectives were as follows:

- Provide a concise assemblage of available information on costs of current and emerging technologies for treatment and disposal of hazardous wastes. The technologies must represent effective physical, chemical and biological processes and must take into account potential process changes and resource recovery.
- Upgrade existing data by gathering additional information from literature sources and equipment manufacturers.
- Develop cost functions to reflect the variations in cost at different levels of control by specific technologies.
- Array the available treatment and disposal options according to their cost-effectiveness for environmental protection.
- Provide qualitative assessments and comparisons of the risk of adverse incidents and complexity of

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implementation

implementation associated with each technological option.

Comparisons of effectiveness were to be subject to the criteria developed by the Office of Solid Waste Management (OSW) for controlling hazardous wastes as promulgated under Subtitle C of RCRA (PL 94-580). Comparisons of cost were to be made on a life cycle basis; taking into account technology, capital and annual operation/maintenance costs and equipment lifetime.

SCOPE

This study is directed to the treatment and disposal of aqueous waste streams emanating from the organic chemicals, inorganic chemicals, and electroplating and metal finishing industries. The disposal of hazardous liquids, as well as sludges and other solids generated by treatment processes, is also considered. Special attention is given to pesticides contained in industrial waste streams.

Table 1 lists the types of chemicals contained in waste streams of the three industries. The organic chemicals industry demonstrates the greatest variety of organic chemicals used in manufacturing of polymers, fibers and other complex organic products (1). Metals appearing in the organic chemicals industry's process effluents are primarily unrecovered catalytic materials, corrosion products, inorganic raw material residues and additives to organic process feedstocks.

The inorganic chemicals industry generates organic and inorganic waste products from a variety of chemical production processes. Mercury-bearing compounds are generated by the mercury-cell process and are generally removed from wastewaters by precipitating as sulfides (2). The diaphragm cell process discharges chlorinated hydrocarbons, asbestos and some lead salts. Chromium is a typical waste constituent emanating from titanium dioxide manufacture, chrome color and inorganic pigment production, and chromate synthesis. Other metals in the inorganic chemical waste streams include lead, copper, nickel, arsenic compounds and antimony.

Electroplating wastes are typically generated in relatively small volumes. They are, therefore, treated by small-scale systems and/or transported for processing at a hazardous waste disposal facility. Electroplating sludges may be processed for recovery of certain metals or disposed of directly in a secure landfill. Significant constituents of electroplating wastes are acids and metals such as chromium, zinc, copper, nickel, iron and

TABLE 1. CHEMICALS CONTAINED IN WASTE STREAMS OF THREE INDUSTRIES

Hazardous Waste Category	Industry		
	Organic Chemicals	Inorganic Chemicals	Electroplating/ Metal Finishing
Organic Chemicals	Phenols and cresols, ethers, halogenated aliphatics, polycyclic aromatic hydrocarbons, monocyclic aromatics, nitrosamines, PCBs, phthalate esters	Chlorinated hydrocarbons	Degreasing solvents, chlorinated hydrocarbons
Metals, Metal Salts, Complexes, etc.	Misc. (used in catalysts)	Hg, HgCl, HgS, Pb, Cr, Cu, Ni, Sb, chromates, sodium-calcium, calcium-fluoride, ferric ferrocyanide, ferric arsenate, arsenic chlorides, nickel hydroxide, lead salts, arsenic trisulfide	Pb, Cr, Cu, Ni, An, Cd, Pd
Non-Metal Inorganics	Various	Asbestos Phosphorus sulfide Phosphorus trichloride	Cyanides Fluorides
Acids Caustics	Misc. acids Misc. caustics (used in production reactions)	Hydrofluoric acid Sulfuric acid Hydrochloric acid Caustics	Sulfuric acid Hydrochloric acid Caustics
Pesticides	Certain halogenated aliphatics	Inorganic pesticide manufacture (mainly metals; Cu, Pb, Zn)	Chlorinated hydrocarbons

Source: SCS Engineers.

cyanides in solution, either as simple ions or as cyanide complexes (3,4,5). Precleaning of components to be plated or finished is often necessary in order to remove any greases or imperfections which will disrupt the finish. Degreasing solvents and certain chlorinated hydrocarbons are contaminated by this procedure and must be recovered or disposed. Pickling baths and alkaline cleaners are also periodically exhausted and changed out.

Tables 2 and 3 summarize the waste flows included in process discharges from typical plants within the three industry categories for one EPA region. The data in Table 2 were used to determine the "real world" range of flows which can be expected from specific industries. All technologies included in this report were analyzed within these ranges. Note that aqueous electroplating discharges are predominately indirect (e.g., to municipal treatment systems). Therefore, special consideration is given to these wastes in terms of possible pretreatment requirements.

REQUIREMENTS UNDER RCRA

On December 18, 1978, the U.S. Environmental Protection Agency issued proposed rules under Sections 3001, 3002 and 3004 of the Solid Waste Disposal Act as substantially amended by the Resource Conservation and Recovery Act of 1976 [PL 94-580 (October 21,1976)]. Of particular relevance to this project was Section 3004 which addresses standards affecting owners and operators of hazardous waste treatment, storage and disposal facilities. As indicated in the overview of Subtitle C (Federal Register, Vol. 43, No. 243, Monday, December 18, 1978), these standards define the levels of human health and environmental protection to be achieved by these facilities. Facilities on a generator's property, as well as off-site facilities, are covered.

The regulatory structure of Section 3004 (40 CFR 250 Subpart D) emphasizes design and operating standards. Technologies or unit processes specifically regulated include incineration, landfills, surface impoundments and basins. Section 250.45-6 also addresses requirements for chemical, physical, and biological treatment facilities. Appendix A provides detail on the proposed rules for each type of operation.

Each technology included in this report is designed to meet the design and operation limitations stipulated by RCRA. The incinerator is equipped with secondary burners and a scrubber module. The landfill includes provisions for avoiding groundwater contamination, monitoring and collecting leachate and controlling surface runoff onto and away from the landfill area using diversion structures. All lagoon systems (aerated lagoon

TABLE 2. FLOW RATES OF PROCESS DISCHARGES FROM PLANTS WITHIN THE ORGANIC CHEMICALS INDUSTRIES IN REGION 10

Discharge*	SIC code†	Flow m^3/D	Flow gpd	Flow l/s	Flow gpm	No. of plants
Direct	2865	Low: $1.2x10^2$ Avg: $2.7x10^3$ High: $5.3x10^3$	$3.4x10^4$ $7.2x10^5$ $1.4x10^6$	Low: 5.7 Avg: $1.2x10^2$ High: $2.3x10^2$	$2.4x10^1$ $5.0x10^2$ $9.7x10^2$	2
Indirect	2865	--	--	--	--	None
Direct	2869	Low: $4.5x10^1$ Avg: $3.8x10^3$ High: $1.3x10^4$	$1.2x10^4$ $1.0x10^6$ $3.5x10^6$	Low: 2.1 Avg: $1.6x10^2$ High: $5.7x10^2$	8.3 $7.0x10^2$ $2.4x10^3$	5
Indirect	2869	$1.4x10^2$	$3.7x10^4$	6.1	$2.6x10^1$	1

* Direct discharge = discharge of effluents to a navigable waterway

Indirect discharge = discharges to a direct discharger

† SIC Code	Industry (Organic)
2865	Cyclic crudes and intermediates
2869	Industrial organic chemicals

TABLE 3. FLOW RATES OF PROCESS DISCHARGES FROM PLANTS WITHIN THE INORGANIC CHEMICALS AND ELECTROPLATING INDUSTRIES IN EPA REGION 10

Discharge*	SIC code†	Flow m^3/D	Flow gpd	Flow l/s	Flow gpm	No. of plants
Direct	2812	Low: 5.7×10^3 Avg: 2.2×10^4 High: 4.5×10^4	1.5×10^6 5.8×10^6 1.2×10^7	Low: 2.4×10^2 Avg: 9.5×10^2 High: 1.9×10^3	1.0×10^3 4.0×10^3 8.3×10^3	7
Indirect	2812	--	--	--	--	None
Direct	2813	Low: 1.7×10^1 Avg: 2.2×10^1 High: 2.7×10^1	4.5×10^3 5.9×10^3 7.2×10^3	Low: 0.7 Avg: 1.0 High: 1.2	3.1 4.1 5.0	2
Indirect	2813	Low: 2.5×10^1 Avg: 1.5×10^2 High: 2.6×10^2	6.7×10^3 3.9×10^4 6.9×10^4	Low: 1.1 Avg: 6.3 High: 1.1×10^1	4.7 2.7×10^1 4.8×10^1	4
Direct and Indirect	2816	--	--	--	--	None
Direct	2819	Low: 5.3×10^2 Avg: 1.7×10^4 High: 5.0×10^4	1.4×10^5 4.6×10^6 1.3×10^7	Low: 2.3×10^1 Avg: 7.6×10^2 High: 2.1×10^3	9.7×10^1 3.2×10^3 9.0×10^3	8
Indirect	2819	Low: 1.4×10^2 Avg: 2.6×10^2 High: 3.8×10^2	3.6×10^4 6.8×10^4 1.0×10^5	Low: 5.9 Avg: 1.1×10^1 High: 1.6×10^1	2.5×10^1 4.7×10^1 6.9×10^1	2

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TABLE 3. (Continued)

Discharge*	SIC code†	Flow m^3/D	Flow gpd	Flow l/s	Flow gpm	No. of plants
Direct	3471	--	--	--	--	None
	3479	--	--	--	--	None
Indirect	3471	Low: 4.5×10^{-1} Avg: 2.3×10^{2} High: 2.6×10^{3}	1.2×10^{2} 6.2×10^{4} 7.0×10^{5}	Low: 2.0×10^{-2} Avg: 10.7 High: 11.4×10^{1}	8.3×10^{-2} 4.4×10^{1} 4.9×10^{2}	85
	3479	Low: 4.5×10^{-1} Avg: 3.1×10^{1} High: 9.1×10^{1}	1.2×10^{2} 8.2×10^{3} 2.4×10^{4}	Low: 2.0×10^{-2} Avg: 1.4 High: 4.0	8.3×10^{-2} 5.7 1.7×10^{1}	9

* Direct discharge = discharge of effluents to a navigable waterway

Indirect discharge = discharges to a direct discharger

†

SIC Code	Industry (Inorganic)	SIC Code	Industry (Electroplating)
2812	Alkalies and chlorine	3471	Plating & polishing
2813	Industrial gasses	3479	Metal coating and allied services
2816	Inorganic pigment		
2819	Industrial inorganic chemicals		

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and evaporation pond) have a liner system, a leachate detection system, and sufficient freeboard to prevent accidental drainages. Basins are designed to be of sufficient strength and wall thickness to prevent the discharge of waste to navigable waters or groundwater. All uncovered reaction vessels are sized to provide sufficient freeboard to prevent splashing or spillage of hazardous waste during treatment processes (e.g., neutralization, precipitation).

Section 250.43 requires that all facilities with point source discharges to navigable waters, including discharges from leachate collection systems and/or surface water runoff collection systems, comply with all applicable regulations promulgated under the Clean Water Act (PL 92-500). Also, facilities with discharges to municipal sewer systems are required to meet applicable Clean Water Act pretreatment standards. These performance requirements were taken into account during the exercising of the computer models described herein.

APPROACH

Figures 1 and 2 are diagrams of the steps or "subtasks" which were executed during the formulation of the cost and risk models, respectively. Initial work on the cost-effectiveness models involved the identification of the technologies and waste streams to be included in the study.

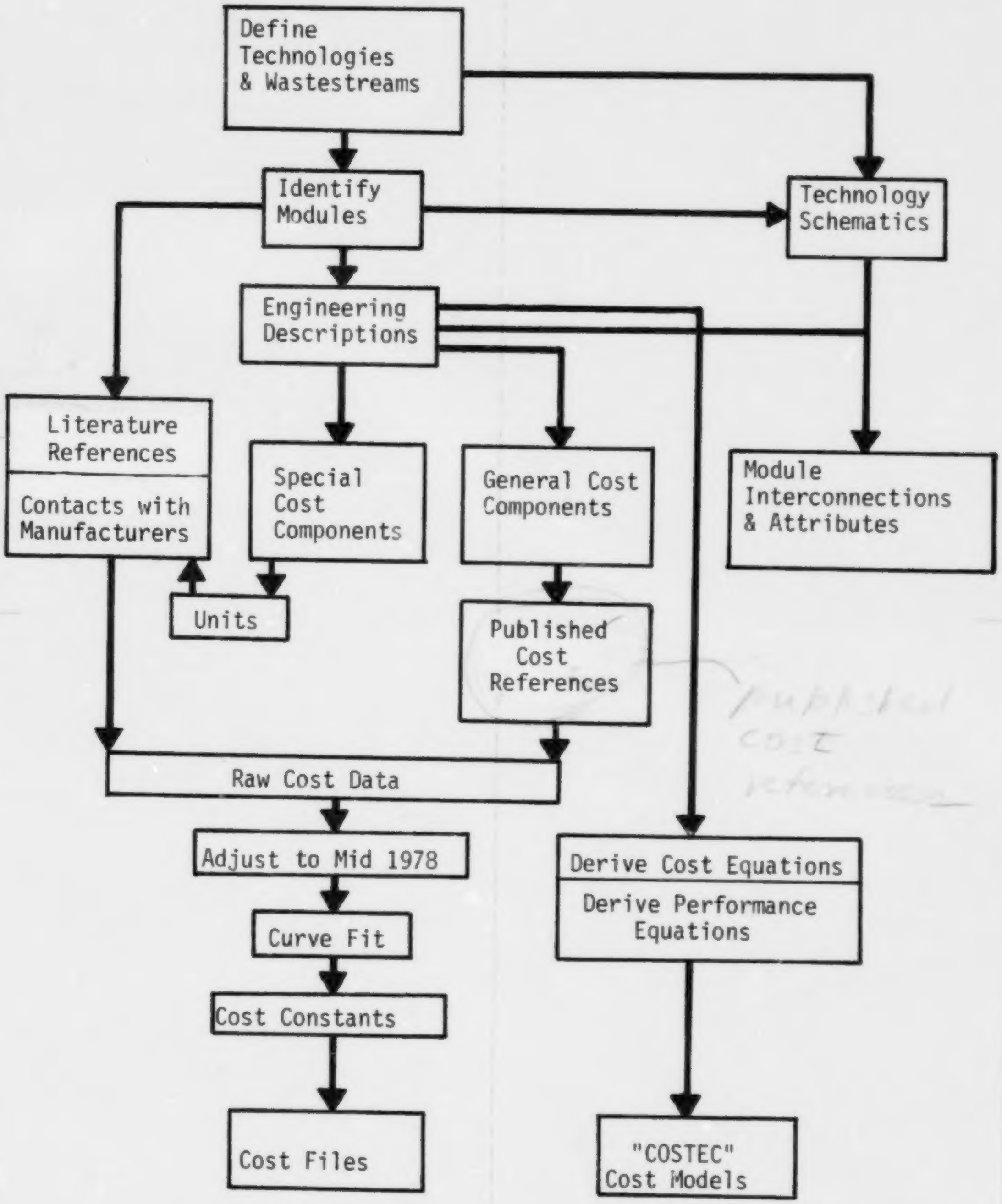
In order to establish a suitable scope for hazardous waste evaluation, three representative industries were selected:

- Organic chemicals
- Inorganic chemicals
- Electroplating and metal finishing.

The selection of these three industries served as a basis for defining the spectrum of hazardous constituents to be evaluated in terms of effectiveness.

To select treatment/disposal technologies for study, a comprehensive list of all known processes was assembled. Each candidate treatment process was then rated according to the following criteria:

1. Applicability within industry categories (according to available references)
2. Presence in typical off-site or municipal treatment processes
3. Availability of cost and performance data
4. Whether the technique is destructive or involves indefinite fixation/storage.


Define Technologies & Wastestreams
Identify Modules
Technology Schematics
Engineering Descriptions
Literature References
Contacts with Manufacturers
Special Cost Components
General Cost Components
Module Interconnections & Attributes
Units
Published Cost References
Raw Cost Data
Adjust to Mid 1978
Curve Fit
Cost Constants
Cost Files
Derive Cost Equations
Derive Performance Equations
"COSTEC" Cost Models

published cost references

Figure 1. Steps for acquiring cost data and deriving computer-assisted cost models. (Source: SCS Engineers)

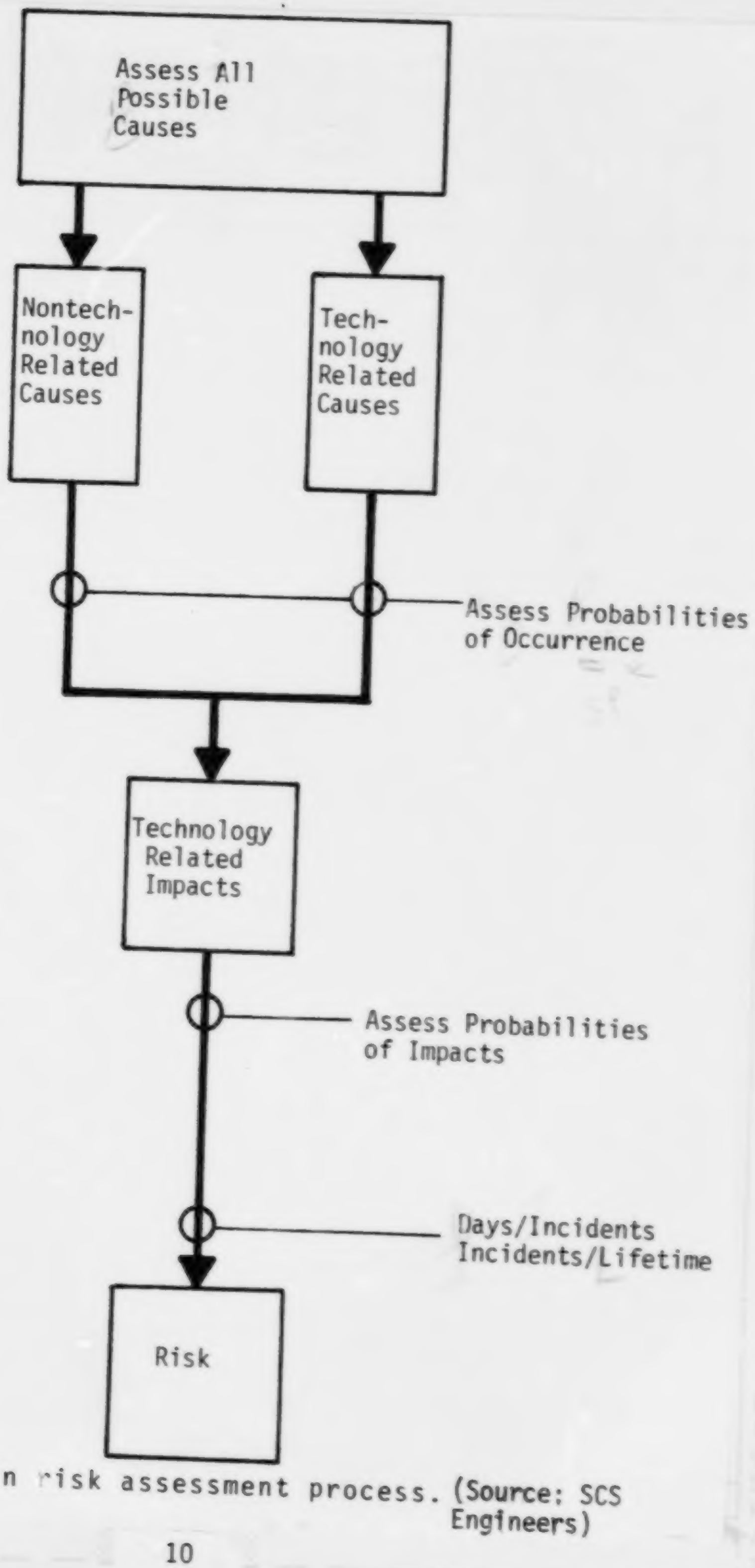

Assess All Possible Causes
Nontechnology Related Causes
Technology Related Causes
Assess Probabilities of Occurrence
Technology Related Impacts
Assess Probabilities of Impacts
Days/Incidents
Incidents/Lifetime
Risk

Figure 2. Steps in risk assessment process. (Source: SCS Engineers)

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Based on the above-described analysis, the following treatment technologies were selected:

Precipitation

- Precipitation/flocculation/sedimentation
- Filtration
- Evaporation
- Distillation
- Dissolved air flotation
- Oil/water separation
- Reverse osmosis
- Ultrafiltration
- Chemical oxidation/reduction
- Hydrolysis
- Aerated lagoon
- Trickling filter
- Waste stabilization pond
- Anaerobic digestion
- Carbon adsorption
- Activated sludge.

Selected disposal technologies included:

- Incineration
- Land disposal
- Chemical fixation
- Encapsulation
- Evaporation pond.

precipitation

Once the technologies and waste streams were identified, the technologies were analyzed to identify significant unit processes or "modules". For example, an important chemical process for treatment of electroplating wastes is precipitation/flocculation/sedimentation. The significant modules associated with this technology were found to be:

- Flash mixer
- Flocculators
- Chemical storage and feed
- Sedimentation basin
- Sludge dewatering
- Piping and valves
- Various pumps.

Detailed assessments of each technology yielded engineering descriptions and process flow schematics. This material is included in the main body of this report. Once the technologies were defined in terms of their components, data gathering and further engineering assessments were conducted in order to 1) assemble comprehensive and accurate cost files for technology and module components, and 2) derive cost and performance equations relating the cost of individual components to scaling factors (e.g., flow, waste loadings, etc.) and system variables

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(e.g., basin volume, retention time, etc.). The cost files (capital and operation/maintenance), the cost and performance equations and the executive*(control) programs were then coded and entered in a modified Fortran IV format for exercising and analysis.

The risk analyses included assessments of potential loss due to catastrophic events, unexpected downtime and/or equipment damage, and potential for adverse environmental impacts associated with the existence and operation of each technology.

The method of analysis varied for each category of risk. In determining the potential loss due to catastrophic events, for example, consideration must be given to technology-dependent factors (susceptibility) and independent factors (natural phenomenon). The probability of occurrence of catastrophic events is independent of the technology. Catastrophic events can be related to geographical location. This fact is taken into account in the risk assessment process.

Downtime risks, on the other hand, can have a variety of causes with technology-related probabilities of occurrence. Some causes of problems (such as chemical supply or labor) are independent of the type of technology, although their impacts are not. Other causes, such as system reliability, are inherent in the type of technology. The same is true for the causes, probabilities and results of unexpected equipment damage.

The causes of adverse environmental impacts associated with each technology are relatively well defined in terms of the quantities and qualities of discharges to the surrounding environment. The probability and nature of the impacts resulting from such discharges are much more difficult to identify. The ramifications of discharges are not always directly related to the technology but rather to secondary environmental factors. The variety of possible impacts is difficult to predict and confounds a technology-specific comparison. Therefore, emphasis is given to the existence or absence of potential causes of such impacts; the probability, nature and relative importance of impacts is discussed in terms of criteria under RCRA and possible site-specific issues facing the user of this report.

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*The Executive Program: Controls user interactions with the models and coordinates the system function and information exchange and summary.

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SECTION 2

CONCLUSIONS

The following conclusions are based upon the cost data and analytical methods as presented in this report. Observations concerning treatment and disposal alternatives are limited to the configurations and applications described herein. The term "cost-effective" is used to describe a unit process or technology which demonstrates the least cost per unit of waste processed or disposed. Such a determination is made by comparing the life cycle average costs of alternative processes or technologies.

Conclusions are presented in three subsections: treatment processes, disposal processes and risks. Although chemical fixation, encapsulation and evaporation ponds may be viewed as pre-disposal treatment processes, they are included as disposal because of their close association with the land disposal process.

The costs cited herein are from life cycle cost evaluations conducted for each technological alternative. Where applicable, unit and installed equipment costs were based on those given for the City of Chicago and expressed as mid-1978 values.

TREATMENT PROCESSES

- Precipitation/flocculation/sedimentation as a treatment process is cost effective [\$0.45-0.31/m^3 (\$1.72-1.16/1,000 gal) at all scales of operation] for removal of many organic compounds, metals and non-metal inorganic compounds to meet water pollution control standards; on a life cycle cost basis. This compares with evaporation(\$2.24/m^3), distillation (\$3.44/m^3), reverse osmosis (\$1.77/m^3), ultrafiltration (\$0.80/m^3), carbon adsorption (\$5.35/m^3), chemical oxidation/reduction (\$1.15/m^3) and filtration (\$0.61/m^3). Hydrolysis is limited in application to specific organic compounds (e.g., pesticides) and certain non-metal organics. Oil/water separation is also limited in its applicability to only the less soluble, concentrated oils.

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1.72-1.16 —

all scales of operation]

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- Evaporation, reverse osmosis or ultrafiltration can be applied where precipitation/flocculation/sedimentation or standard filtration are not cost effective. Of the three, ultrafiltration has the lowest life cycle cost [\$0.74/m^3 (\$2.81/1,000 gal) at a scale of 315.5 l/s (5,000 GPM)]. Ultrafiltration is a cost effective alternative to reverse osmosis [\$0.74 vs. \$1.92/m^3 at a scale of 315.5 l/s]. However, it cannot be applied in cases where particle size and other waste characteristics interfere with adequate removal.

- Of the solids separation processes, dissolved air flotation was found to have the lowest life cycle cost for the Chicago example [\$0.33/m^3 (\$1.26/1,000 gal) at a scale of 63 l/s (1,000 GPM)]. However, dissolved air flotation can only remove certain types of particles and is not a direct alternative to standard filtration, ultrafiltration or reverse osmosis. Of these, standard filtration demonstrated the lowest cost [\$0.61/m^3 (\$2.31/1,000 gal) at a scale of 63 l/s (1,000 GPM)].

- Distillation demonstrates a high life cycle cost [\$3.44/m^3 (\$13.02/1,000 gal) at a scale of 63 l/s (1,000 GPM)] and cannot be applied to wastes which can be treated by less costly technologies such as evaporation [\$2.24/m^3 (\$8.48/1,000 gal)].

- Although limited to certain pesticides (e.g., organophosphates) and inorganic materials (e.g., titanium sulfate), hydrolysis is a promising technology for destruction of problematic wastes. Cost analysis indicates that the technique is cost effective, demonstrating a life cycle cost of \$0.22/m^3 (\$0.82/1,000 gal) at a scale of 63 l/s (1,000 GPM).

- Oil/water separation is only applicable to easily separable oils and may require further effluent treatment if oil is emulsified. Where the process is capable of meeting discharge limitations, it is a cost effective treatment technique; demonstrating a life cycle cost of \$0.13/m^3 (\$0.48/1,000 gal) at a scale of 63 l/s (1,000 GPM).

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- Five biological treatment processes for aqueous wastes are analyzed (dissolved air flotation, aerated lagoon, trickling filter, waste stabilization pond and activated sludge). The cost models for each process are constrained by the same waste input characteristics, nutrient additions, performance requirements and operational conditions. All technologies are designed to conform with standards promulgated under Section 3004 of RCRA. For biodegradable organic constituents, dissolved air flotation has the lowest life cycle average cost at all levels of throughput. Anaerobic Digestion, although also considered a biological process, is only applied to organic sludges containing low levels of toxic compounds. The life cycle cost for this process is $1.36/m^3$ ($5.14/1,000 gal.) of sludge processed at a scale of operation of 63 l/s (1,000 GPM).

DISPOSAL PROCESSES

- Cost-effective disposal processes are land disposal for solids, evaporation ponds for liquid wastes (meeting the limitations set by RCRA for volatility and reactivity) and incineration for waste streams with sufficient heat value. The life cycle average costs for incineration and land disposal are $565.70 and $340.26/t ($256.55 and $154.34/1,000 lbs) at a disposal rate of 450 kg/hr (1,000 lbs/hr), respectively. The appreciably higher cost for incineration means that only those wastes unsuitable for land disposal (e.g., polychlorinated biphenyls) can be disposed of in a cost-effective manner using this technology.

- Chemical fixation is more costly than encapsulation ($198.41 vs $102.78/t) when appreciable solids are present. At low solids concentrations, chemical fixation is cost-effective.

- Evaporation pond exhibits a life cycle average cost of $0.94/m^3$ ($3.54/1,000 gal) at a scale of 252 and 315 l/s (4,000 and 5,000 GPM). Given a waste with a specific gravity of 2.0, evaporation pond technology represents a cost-effective dewatering technique prior to land disposal (life cycle cost = $0.47 - 0.53/t assuming specific gravity = 2.0).

- Both land disposal and evaporation ponds demonstrate high environmental risks, although these can be significantly reduced by pre-disposal waste solidification using chemical fixation or encapsulation.

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RISK

- Three categories of risk are assessed for each treatment/disposal technology: catastrophic events, downtime and adverse environmental impacts. Catastrophic events pose the highest risk of loss where technologies include high structures (e.g., towers) and/or flammable components. Distillation, carbon adsorption and incineration are most susceptible. Lagoons and land disposal demonstrate the lowest risk.

- Downtime risks are a function of complexity, sensitivity to input changes and operational demands--are lowest for chemical oxidation/reduction, hydrolysis and evaporation ponds. Risk is high for reverse osmosis, ultrafiltration and encapsulation.

- The potential for adverse environmental impact includes potential for impacts on health, surface waters, subsurface environments, air resources and secondary waste outputs. With equal weight given to each of these categories, aerated lagoons and waste stabilization ponds demonstrate the highest risk among the treatment processes. Subsequent effluent treatment by reverse osmosis, ultrafiltration or carbon adsorption can significantly reduce impacts on surface water quality.

ECONOMIES OF SCALE

Significant economies of scale are indicated for the following treatment/disposal technologies according to comparisons of life cycle average costs at various scales of operation.

- Precipitation/flocculation/sedimentation
- Filtration
- Evaporation
- Dissolved air flotation
- Trickling filter
- Waste stabilization pond
- Anaerobic digestion
- Carbon adsorption
- Incineration
- Land disposal.

Other technologies, such as chemical oxidation/reduction, ultrafiltration, oil/water separation, hydrolysis, incineration, activated sludge and aerated lagoon, demonstrate least cost ranges of scale; the life cycle costs per unit throughput becoming less up to a certain size. Then, at larger scales of operation, the costs begin to increase. Reverse osmosis shows increasing costs with increases in scale.

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SECTION 3

RECOMMENDATIONS

- Ultrafiltration is a cost-effective treatment process for a variety of hazardous waste streams not treatable by precipitation/flocculation/sedimentation. Cost and performance constraints associated with commercial-scale applications of the technology should be further researched.

- The use of industrial evaporators for concentration of organic and inorganic aqueous wastes is promising and less costly than distillation. Commercial-scale evaporator installations capable of using concentrated wastes as a heat source (which are not presently utilized) should be studied.

- Chemical fixation as a pre-disposal solidification process is commonly provided on-site through the use of portable equipment. Additional investigation is necessary to quantify the economic and technical constraints of a commercial-scale permanent installation.

- Encapsulation is presently being studied on a pilot scale. Additional research is necessary to identify all capital and operation/maintenance costs associated with a commercial-scale operation.

- Research should continue towards developing economical methods for carbon regeneration in large-scale carbon adsorption plants. If the capital and operational costs associated with regeneration are significantly reduced, carbon adsorption will be competitive with alternative treatment schemes.

- Additional land disposal techniques and incineration technologies should be modeled and compared on a life cycle cost basis. Landfarming and molten salt incineration are two examples.

- The hazardous waste treatment/disposal cost model (called "COSTEC") developed during this study should be augmented with additional capabilities. These include:

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- Improvement of the executive program for automatically linking the individual unit process models. Complete automation of the "COSTEC" system would facilitate a greater variety of technology comparisons.

- Development of additional unit process cost-performance models so additional treatment and disposal technologies can be analyzed, (such as in addition to the secure hazardous waste landfill modeled herein) landfarming of industrial wastes and co-disposal with municipal refuse. Other promising thermal destruction processes, besides the rotary kiln, include molten salt, pyrolysis, fluidized bed, multiple hearth, multiple chamber and liquid waste incinerator. Solidification processes recommended for inclusion are silicate, cement base, lime base, thermoplastic and organic base processes. Specific chemical neutralization processes should also be modeled.

- Expansion of existing cost models to include additional performance details. This can be accomplished using two methods: 1) accumulate additional performance data for specific waste constituents in a designated computer file (similar to the cost data files used in this study), and 2) derive and include equations which model the stoichiometry and kinetics of actual treatment/disposal transformations.

- The computerized cost models derived and used in this study can readily be used to conduct sensitivity analyses, to study the influence of changes in unit costs, in system variables and other factors on the total technology costs. Such investigations should be conducted in order to improve the understanding of technology cost dynamics.

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SECTION 4

HAZARDOUS WASTE MANAGEMENT ALTERNATIVES

Low cost and effective treatment and/or disposal alternatives can be selected by using the tools and data presented in this report. As a typical example, unit cost data for capital and operation/maintenance requirements are assembled for the greater Chicago area (Appendices B and C). The results of the example model analyses described in Section 6 (Technologies for Hazardous Waste Treatment and Disposal) are summarized in this section to assist engineers and decision makers in selecting cost-effective alternatives.

TREATMENT/DISPOSAL ALTERNATIVES PER WASTE STREAM

Table 3 illustrates the applicability of treatment and disposal technologies to the waste categories.

Selected Alternatives

Results of the simple average and life cycle average cost calculations for each treatment and disposal technology are shown on Tables 4 and 5 in metric and standard units of expression, respectively. The scales of operation for incineration, land disposal, chemical fixation and encapsulation are expressed in terms of kilograms and pounds per hour. All other technology scales are in terms of liters per second or gallons per minute.

Since each technology is constrained to similar waste inputs and performance requirements, it is possible to utilize the results in Tables 4 and 5 to compare alternatives for certain waste treatment/disposal needs. Figures 3 through 7 facilitate this comparison based on the alternative treatment/disposal technologies (for each waste stream) categorized in Table 3.

Results of the risk analysis described in Section 7 are summarized in Table 6. Initial identification of viable treatment and/or disposal options are based on cost and performance. Comparisons based on risk should be considered as secondary or confirmatory to the cost assessment.

Of the biological treatment processes analyzed, dissolved air flotation exhibits the lowest life cycle average costs.

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TABLE 4. APPLICABILITY OF TREATMENT AND DISPOSAL TECHNOLOGIES TO CATEGORIES OF HAZARDOUS WASTE

	Hazardous Waste Category					
	Organic Chemicals		Metals	Non-Metal Inorganics	Acids Caustics	Pesticides
	Biodegradable	Non-biodegradable				
Treatment	Dissolved Air Flotation Aerated Lagoon Trickling Filter Waste Stab. Pond Activated Sludge Anaerobic Digestion Hydrolysis	Evaporation Distillation Oil/Water Sep. Reverse Osmosis Ultrafiltration Hydrolysis Carbon Adsorption Precip./Floc./Sed.	Precip/Floc./Sed. Reverse Osmosis Ultrafiltration Chem. Oxid./Red.	Precip./Floc./Sed. Filtration Evaporation Chem. Oxid./Red. Hydrolysis	Chem. Oxid./Red.	Hydrolysis
Solidification	Chemical Fixation Encapsulation					
Disposal	Incineration Land Disposal Evaporation Pond					

(SOURCE: SCS ENGINEERS)

TABLE 5. COST COMPARISONS AMONG TREATMENT AND DISPOSAL TECHNOLOGIES: METRIC UNITS

Technology	Life	Simple Average Cost ($/m³) * at l/s					Life Cycle Average Cost ($/m³)* at l/s				
		63.1	126.2	189.3	252.4	315.5	63.1	126.2	189.3	252.4	315.5
Precipitation/Flocculation/Sedimentation	10	0.70	0.57	0.51	0.49	0.47	0.45	0.37	0.33	0.32	0.31
Filtration	10	0.97	0.82	0.73	0.67	0.64	0.61	0.52	0.46	0.43	0.41
Evaporation	5	2.73	2.49	2.41	2.37	2.35	2.24	2.04	1.98	1.95	1.93
Distillation	5	4.19	4.32	4.32	4.32	4.33	3.44	3.53	3.54	3.54	3.55
Flotation	10	0.52	0.43	0.38	0.35	0.34	0.33	0.27	0.24	0.22	0.21
Oil/Water Separator	10	0.20	0.13	0.12	0.12	0.13	0.13	0.08	0.07	0.07	0.08
Reverse Osmosis	7	2.39	2.48	2.54	2.54	2.59	1.77	1.84	1.88	1.88	1.92
Ultrafiltration	7	1.07	0.89	0.95	0.95	0.99	0.80	0.66	0.71	0.71	0.74
Chemical Oxidation/Reduction	5	1.40	1.20	1.19	1.38	1.64	1.15	0.99	0.98	1.13	1.35
Hydrolysis	5	0.26	0.22	0.20	0.20	0.20	0.22	0.18	0.16	0.16	0.17
Aerated Lagoon	15	1.40	1.01	0.87	1.03	1.15	0.69	0.50	0.43	0.51	0.57
Trickling Filter	15	1.24	1.01	0.96	0.87	0.84	0.63	0.51	0.49	0.44	0.43
Waste Stab. Pond	5	1.18	1.04	0.98	0.96	0.94	0.98	0.87	0.82	0.80	0.78
Anaerobic Digestion	10	2.08	1.83	1.73	1.69	1.66	1.36	1.20	1.13	1.11	1.09
Carbon Adsorption	7	7.25	4.34	3.35	2.90	2.61	5.35	3.21	2.48	2.14	1.93
Activated Sludge	10	1.28	0.94	0.82	1.06	1.28	0.81	0.60	0.53	0.68	0.82
Evaporation Pond	20	2.37	2.17	2.09	2.05	2.05	1.06	0.98	0.95	0.94	0.94
		Simple Average Cost ($/t)† at kg/hr					Life Cycle Average Cost ($/t)† at kg/hr				
		453.6	907.2	1360.8	1814.4	2268.0	453.6	907.2	1360.8	1814.4	2268.0
Incineration	5	683.33	657.60	650.70	646.81	647.48	565.70	544.44	538.77	535.55	536.15
Land Disposal	20	859.67	518.40	392.60	329.37	291.80	340.26	201.19	150.73	125.35	110.25
Chemical Fixation With Solids	NA	198.41	198.41	198.41	198.41	198.41	198.41	198.41	198.41	198.41	198.41
Chemical Fixation Without Solids	NA	52.91	52.91	52.91	52.91	52.91	52.91	52.91	52.91	52.91	52.91
Encapsulation	7	136.66	125.18				102.78	94.51			

* $\$/m^3 = \$/1,000$ gal. x 0.2642.
† $/t = $/1,000 lbs. x 2.205.

(Source: SCS Engineers)

TABLE 6. COST COMPARISONS AMONG TREATMENT AND DISPOSAL TECHNOLOGIES: STANDARD UNITS

Technology	Life	Simple Average Cost ($ per 1,000 gal.)* at GPM					Life Cycle Average Cost ($ per 1,000 gal.)* at GPM				
		1,000	2,000	3,000	4,000	5,000	1,000	2,000	3,000	4,000	5,000
Precipitation/Flocculation/Sedimentation	10	2.65	2.16	1.94	1.85	1.79	1.72	1.40	1.26	1.20	1.16
Filtration	10	3.66	3.12	2.75	2.54	2.43	2.31	1.97	1.74	1.61	1.54
Evaporation	5	10.33	9.43	9.12	8.98	8.89	8.48	7.74	7.49	7.37	7.30
Distillation	5	15.86	16.36	16.37	16.36	16.40	13.02	13.39	13.41	13.40	13.43
Flotation	10	1.98	1.62	1.43	1.33	1.27	1.26	1.04	0.92	0.85	0.81
Oil/Water Separator	10	0.76	0.51	0.44	0.44	0.48	0.48	0.32	0.28	0.28	0.30
Reverse Osmosis	7	9.05	9.40	9.61	9.62	9.79	6.71	6.97	7.12	7.13	7.25
Ultrafiltration	7	4.04	3.36	3.61	3.61	3.76	3.02	2.51	2.70	2.70	2.81
Chemical Oxidation/Reduction	5	5.31	4.56	4.52	5.23	6.22	4.36	3.74	3.71	4.29	5.10
Hydrolysis	5	0.99	0.83	0.75	0.74	0.76	0.82	0.69	0.62	0.62	0.63
Aerated Lagoon	15	5.30	3.81	3.31	3.89	4.35	2.62	1.89	1.64	1.93	2.15
Trickling Filter	15	4.70	3.82	3.63	3.30	3.19	2.37	1.93	1.84	1.68	1.63
Waste Stab. Pond	5	4.45	3.94	3.71	3.63	3.54	3.70	3.28	3.09	3.02	2.95
Anaerobic Digestion	10	7.88	6.91	6.53	6.41	6.28	5.14	4.53	4.29	4.21	4.13
Carbon Adsorption	7	27.43	16.43	12.69	10.96	9.89	20.26	12.14	9.38	8.10	7.31
Activated Sludge	10	4.84	3.54	3.11	4.02	4.84	3.08	2.28	2.00	2.57	3.10
Evaporation Pond	20	8.99	8.20	7.90	7.75	7.75	4.01	3.71	3.60	3.54	3.54
		Simple Average Cost ($ per 1,000 lbs.) † at lbs/hr					Life Cycle Average Cost ($ per 1,000 lbs.) † at lbs/hr				
		1,000	2,000	3,000	4,000	5,000	1,000	2,000	3,000	4,000	5,000
Incineration	5	309.90	298.23	295.10	293.34	293.64	256.55	246.91	244.34	242.88	243.15
Land Disposal	20	389.94	235.14	178.08	149.40	132.36	154.34	91.26	68.37	56.86	50.01
Chemical Fixation With Solids	NA	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00
Chemical Fixation Without Solids	NA	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00
Encapsulation	7	61.99	56.90				46.62	42.87			

*\$/1,000 gal. = $\$/m^3 \times 3.785$.
†\$/1,000 lbs. = \$/t x 0.453.

(Source: SCS Engineers)

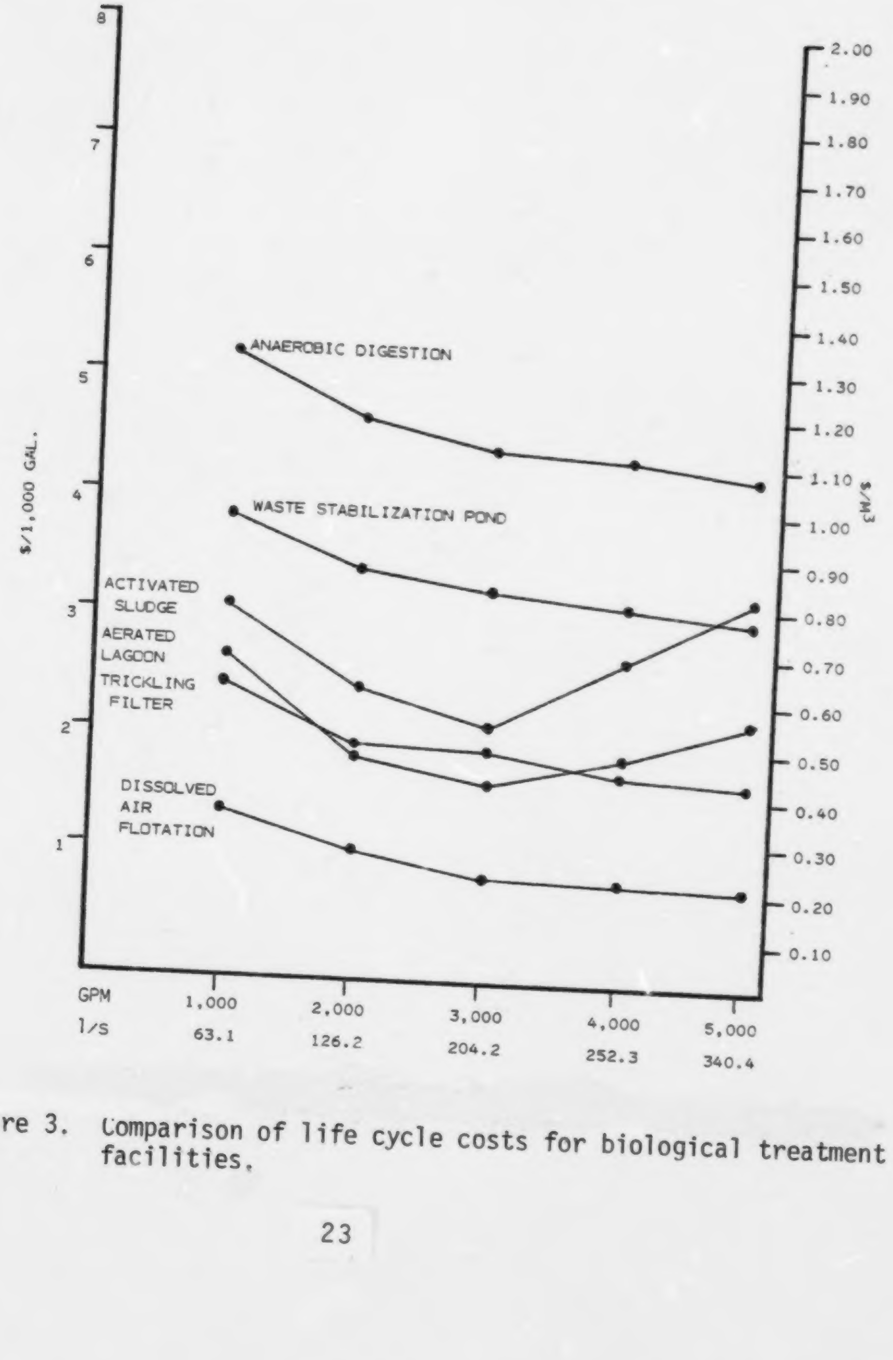

Figure 3. Comparison of life cycle costs for biological treatment facilities.

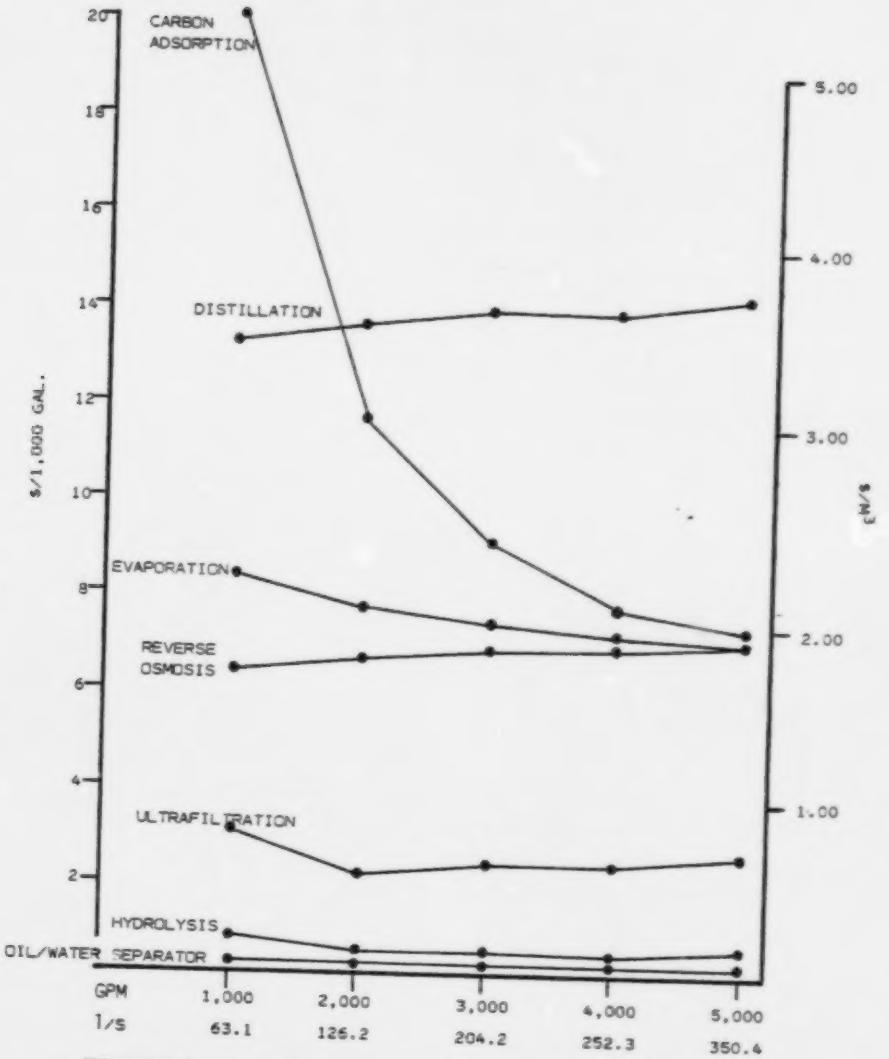

Figure 4. Comparison of life cycle costs for physical/chemical treatment facilities for nondegradable organic wastes.

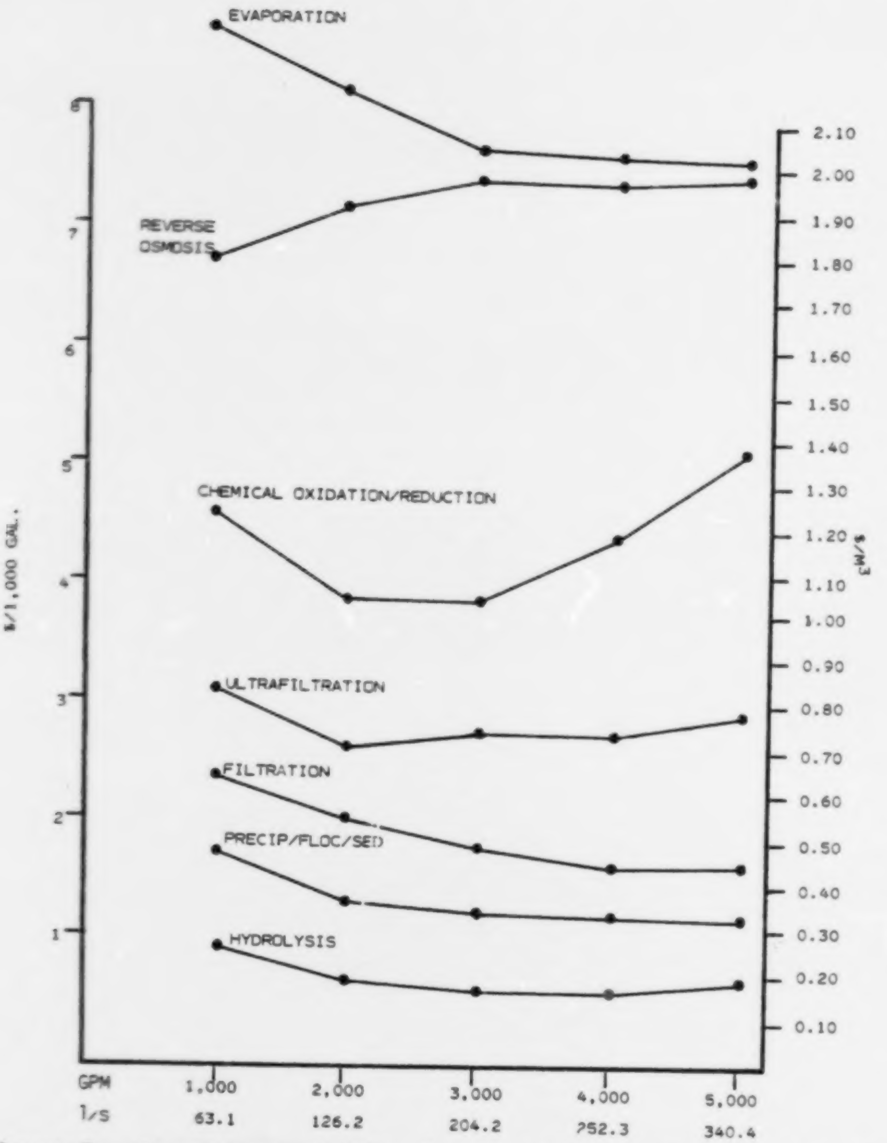

Figure 5. Comparison of life cycle costs for physical/chemical treatment processes for inorganic wastes and certain pesticides.

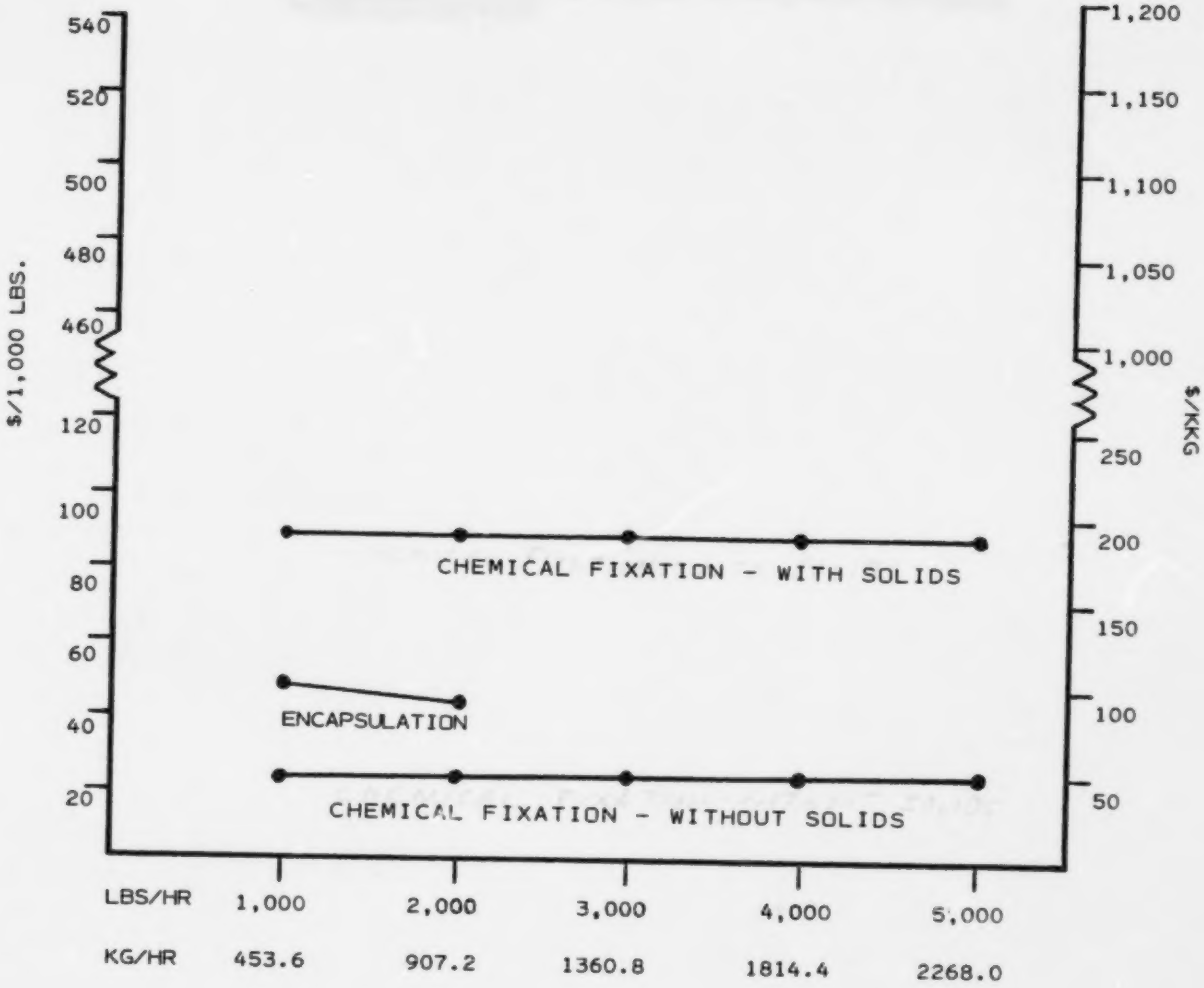

Figure 6. Comparison of life cycle costs for solidification and encapsulation.

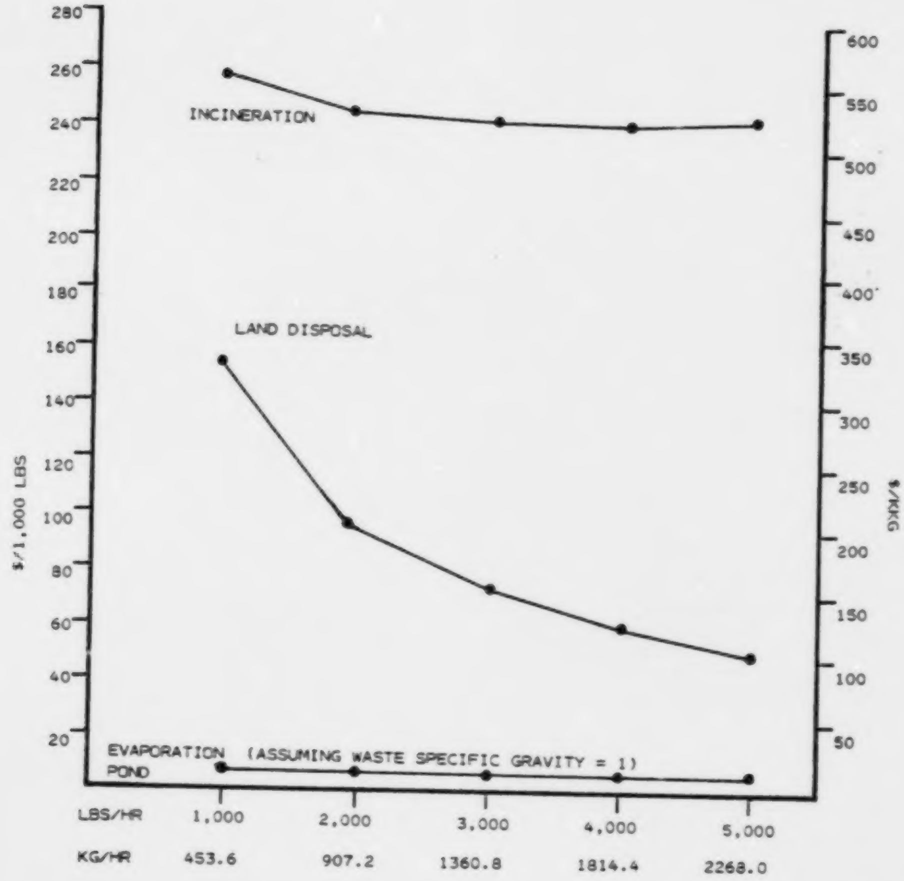

Figure 7. Comparison of life cycle costs for selected disposal technologies,

TABLE 7. SUMMARY OF RISKS ASSOCIATED WITH EACH TREATMENT AND DISPOSAL ALTERNATIVE

Technology	Risk (+ = low, - = high) Catastrophic Event	Downtime	Environmental Impact
Precipitation/flocculation/Sedimentation	+	+	-
Filtration	+	+	+
Evaporation	-	-	+
Distillation	-	-	+
Dissolved air flotation	+	+	+
Oil/water separator	+	+	+
Reverse osmosis	-	-	+
Ultrafiltration	-	-	+
Chemical oxidation/reduction	-	+	+
Hydrolysis	-	+	+
Aerated lagoon	+	+	-
Trickling filter	+	+	-
Waste stabilization pond	+	+	-
Anaerobic digestion	+	+	+
Carbon adsorption	-	-	+
Activated sludge	-	-	+
Evaporation pond	+	+	-
Incineration	-	+	-
Land disposal	+	+	-
Chemical fixation	-	-	+
Encapsulation	-	-	+

However, dissolved air flotation will only meet discharge limitations for dilute and readily biodegradable waste constituents. For marginally degradable materials, the least cost option is aerated lagoon systems.

Non-biodegradable organic compounds may be treated by a number of technologies depending on their physical/chemical properties and concentration in the waste stream. Hydrolysis or oil/water separation is the best alternative for relatively concentrated oils and hydrolyzable compounds. Ultrafiltration is a cost-effective treatment technique for concentrating dissolved organics not treatable by precipitation/flocculation/sedimentation.

Precipitation/flocculation/sedimentation as a treatment process is also cost-effective for removal of many metals and non-metal inorganic compounds. Where additional treatment is deemed necessary, ultrafiltration has the lowest life cycle cost for metal or inorganics removal.

Hydrolysis is the best option for elimination of certain waste acids. However, for acids not amenable to the hydrolytic process and for caustics, elimination through neutralization and chemical oxidation/reduction reactions is the best alternative. Hydrolysis is the only technology included in this study which shows significant potential for destruction of certain pesticide compounds.

Two solidification processes, chemical fixation and encapsulation, are included in this study. Encapsulation, an emerging technology, has a comparative life cycle average cost. Actual economies of encapsulation will be proven once it is implemented on a commercial scale.

Of the disposal technologies, incineration is more expensive than land disposal and should be reserved for those wastes unsuitable for other disposal options. Evaporation pond is viewed as a cost-effective method of dewatering aqueous wastes prior to ultimate disposal.

It is often useful to compare the costs of certain technologies applied to liquid wastes or sludges with those capable of handling solids. The simple average and life cycle costs in Tables 6 and 7 may be divided by the specific gravity of liquid wastes to obtain corresponding estimates for a solids loading $(\$/t = \$/m^3 \div s.g.)$

The following technologies are not capable of processing high density wastes:

- Reverse osmosis
- Ultrafiltration
- Carbon adsorption

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The biological treatment processes (except anaerobic digestion) include primary settling for removal of high-density waste constituents. Solids from hazardous waste treatment facilities are often compatible with land disposal at a secure landfill or incineration at controlled facilities.

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SECTION 5

PROCEDURE FOR COST ANALYSIS

It is the purpose of this report to provide guidelines and tools enabling the user to 1) obtain cost estimates for a predesignated hazardous waste management technology, and 2) compare management alternatives to identify cost-effective configurations for treatment/disposal requirements under RCRA. In order to meet these objectives, this report has been designed to provide cost data without excessive volume or complicated presentations. The report is also designed to provide interactive support for making calculations and to enable the user to derive his/her own comparisons to meet specific needs or interests.

BACKGROUND: DERIVATION OF THE TECHNOLOGY COST DATA

technology estimate

The methods applied by the user in deriving tailored comparisons parallel the methods used for deriving the costs presented in the technology estimates in Section 6. It is, therefore, imperative that the user understand how the cost data is compiled, how it is used to determine unit process (module) costs, and how it is summed to yield cost estimates on a technology (aggregates of modules) basis.

Figure 8 illustrates how the unit capital and operation/maintenance cost data (Appendices B and C, respectively) are utilized in association with the appropriate equation form (Appendix D) and derived component quantity (e.g., square feet of land, cubic yards of concrete, etc.) to generate a cost at a given scale of operation. These component costs are then summed within the cost categories (e.g., land, labor, etc.) to yield costs on a modular or unit process level. Assuming that the individual modules can be assembled using piping, duct work, electrical hookup, etc., to formulate complete treatment technologies, the values for each cost category are summed at the technology level. The total process cost is estimated from the sum of the individual installed equipment module costs making up the process. Appendix E includes brief descriptions of the thirty-five modules used in this report. Table 8 is a matrix of modules included in each of the technologies considered. Pumps and piping are also included in the cost analyses, though not considered as unit processes.

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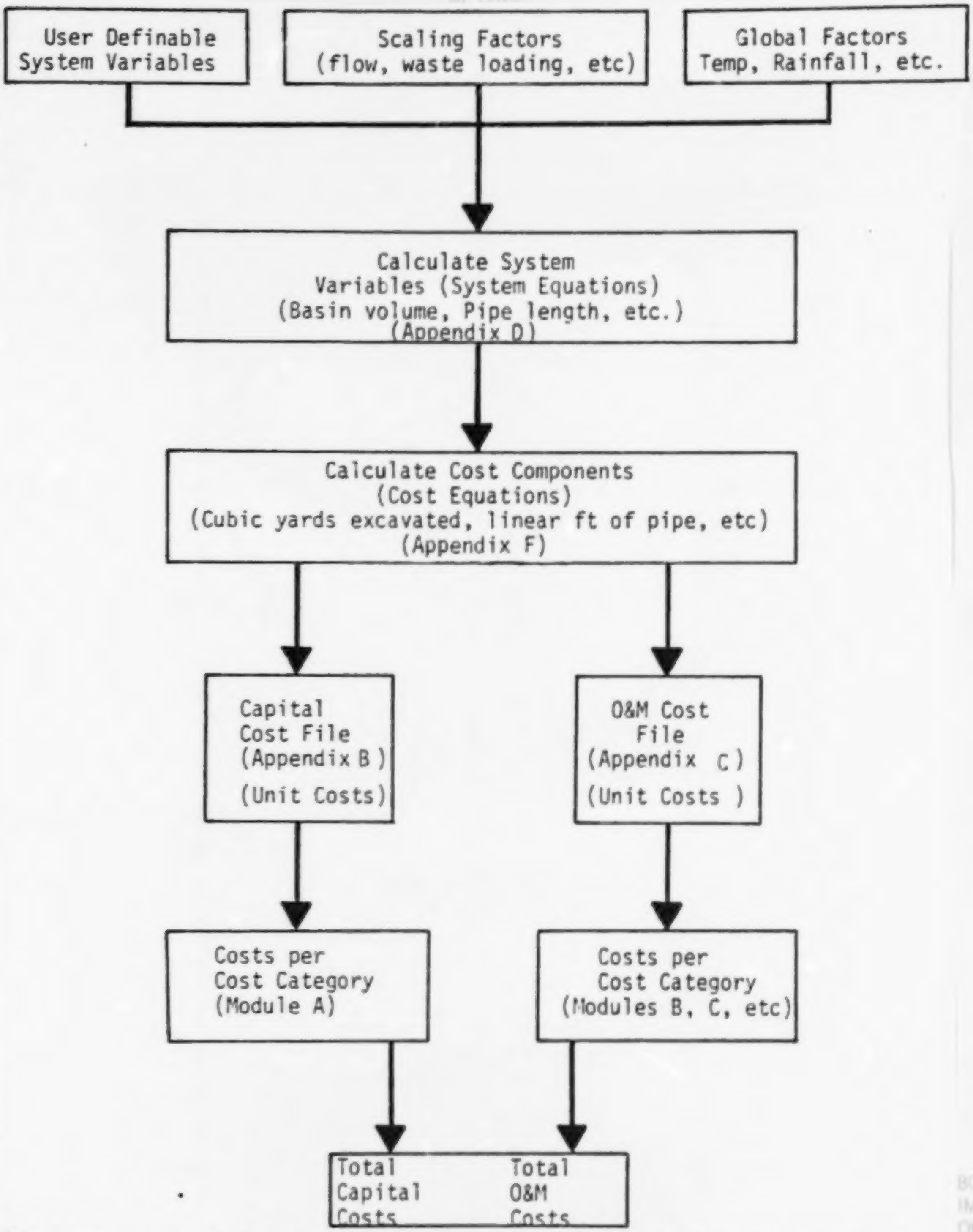
User Definable
System Variables
Scaling Factors
(flow, waste loading, etc)
Global Factors
Temp, Rainfall, etc.
Calculate System
Variables (System Equations)
(Basin volume, Pipe length, etc.)
(Appendix D)
Calculate Cost Components
(Cost Equations)
(Cubic yards excavated, linear ft of pipe, etc)
(Appendix F)
Capital
Cost File
(Appendix B)
(Unit Costs)
O&M Cost
File
(Appendix C)
(Unit Costs)
Costs per
Cost Category
(Module A)
Costs per
Cost Category
(Modules B, C, etc)
Total
Capital
Costs
Total
O&M
Costs

Figure 8. Derivation of hazardous waste treatment and disposal technology costs. (Source: SCS Engineers)

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TABLE 8. UNIT PROCESS MODULES COMPRISING THE HAZARDOUS WASTE TREATMENT AND DISPOSAL TECHNOLOGIES

TECHNOLOGIES / MODULES	Flocculator	Flash Mixer	Jacketed Flash Mixer	Aerated Lagoon	Aerated Basin	Sludge Digestor	Trickling Filter	Waste Stab. Pond	Chemical Fixation	Incinerator	Sedimentation Basin	Clarifier	Rotary Drum Vacuum Filter	Air Flotation	Oil/Water Separator	Multi-media Filter	Distillation	Evaporator	Reverse Osmosis	Ultrafiltration	Carbon Adsorption	Decanter	Chemical Storage: Gas	Chemical Storage: Liquid	Chemical Storage: Solid	Sludge Equalization	Haz. Waste Land Disposal Site	Encapsulation	Deaerator	Evaporation Pond	Steam Generator	Sludge Digestor
Coagulation/Flocculation/Sedimentation	X	X									X		X											X	X							
Filtration													X			X								X								
Evaporator																		X													X	
Distillation																	X							X							X	
Flotation				X									X	X																		
Oil/Water Separator															X									X								
Reverse Osmosis																			X					X								
Ultrafiltration																				X				X								
Chemical Oxidation/Reduction			X																				X	X	X							
Hydrolysis			X																			X		X					X			
Aerated Lagoon				X							X	X	X											X								
Trickling Filter							X				X	X	X											X								
Waste Stab. Pond								X			X																					
Anaerobic Digestion													X											X		X						X
Carbon Adsorption																					X										X	
Activated Sludge					X						X	X	X											X								
Evaporation Pond																														X		
Incineration										X														X								
Land Disposal																											X					
Chemical Fixation									X																							
Encapsulation																												X				

(SOURCE: SCS ENGINE'RS)

The cost estimating portion of the system depends ultimately on the information contained in the capital and operation and maintenance cost files. Sources for unit construction costs are "Means Engineering Cost Data - 1978", various material and labor cost indices and costs associated with the general literature. Specialty hardware costs were obtained directly from manufacturers. Cost data sources are listed in appendices B & C.

Costs for each component were obtained, where possible, for at least five different scales or levels to consider economies of scale. A curve fit methodology was used involving a series of regressions to fit data points to candidate functional forms, each form being a special case of the general form:

$$\text{COST} = A + B \text{ x } (\text{Units})^{D} \quad 1/C$$

where natural logarithms for "cost" and "units" can be used.

A is the y-intercept for the cost curve, B is the slope, and C and A are the exponents of COST and Units, respectively. As shown in Appendices B and C, the cost component data are assigned in the capital and O&M cost files according to the calculated value of each coefficient in the general equation form. The units of measurement and brief descriptions are also included. The advantage of isolating cost data into distinct files is easy inspection and modification or update of the file contents without affecting other system elements.

The equations required for deriving the component quantities (called "system variable equations") and the performance equations are included in Appendix F. These equations are designed for use in a computer-assisted format and provide more detail than is necessary for conceptual and rapid estimating. Thus, it is assumed that adjustments in the example cost estimates presented herein will be made primarily at the module level and above. Exceptions to this include the following cost components:

- Land costs
- Labor costs
- Energy costs
- Maintenance costs
- Chemical costs.

FORMAT FOR PRESENTATION OF THE TECHNOLOGY COST DATA

The cost information for each technology is presented in Section 6 of this report. The costs are based on mid-1978 information for capital and operation requirements in the greater Chicago, Illinois, area. The first table, which presents detailed capital cost information for a technology at a particular scale of operation, is presented in tabular format. Included are capital costs for each module according to specific cost categories (site preparation, structures, mechanical equipment, etc.). Supplemental capital costs (ancillary to implementing the technology) and the quantity of land required for each module are also specified.

Two sets of curves are then presented. The first group indicates total capital costs for each technology (exclusive of land costs) according to the predominant scaling variable (usually flow). The second group plots the relationship of land quantity to the same scaling variable for the technology.

A similar analysis is presented for the technology operation and maintenance (O&M) costs. The costs per category are listed together with quantitative data on labor requirements, power consumption, chemical demands and other related components. Cost information on administrative overhead, debt service and amortization, and real estate taxes and insurance are also included for the technology at a fixed scale of operation.

In order to provide information on how O&M related quantities and costs fluctuate with scale, a group of curves follow the above tabular summary and show:

- Annual labor costs by labor category
- Annual kilowatt hours of electricity consumed
- Annual maintenance costs
- Annual chemical costs.

To facilitate comparisons among treatment/disposal alternatives, each technology is assessed in terms of its life cycle average cost. All technology costs are based on individual costs for critical modules (unit processes).

Figure 9 shows how first year operating costs for a technology are used to estimate simple average and life cycle average costs over the life of a project (n). In order to permit comparisons among technologies on a life cycle cost basis, a curve is presented showing the computed life cycle average costs at various scales of operation. Life cycle costing is advantageous because it permits all costs (over the life span of the technology) to be included in comparative evaluations.

CONCEPTUAL ESTIMATING OF INSTALLED CAPITAL AND ANNUAL O&M COSTS

In Section 6 of this report, installed hazardous waste treatment and disposal technologies are defined in terms of typical unit processes or "modules", and cost data are provided. Sufficient detail is included so that the user can make modifications in the assumed equipment configurations or scale of operations and derive a specific conceptual estimate. Such

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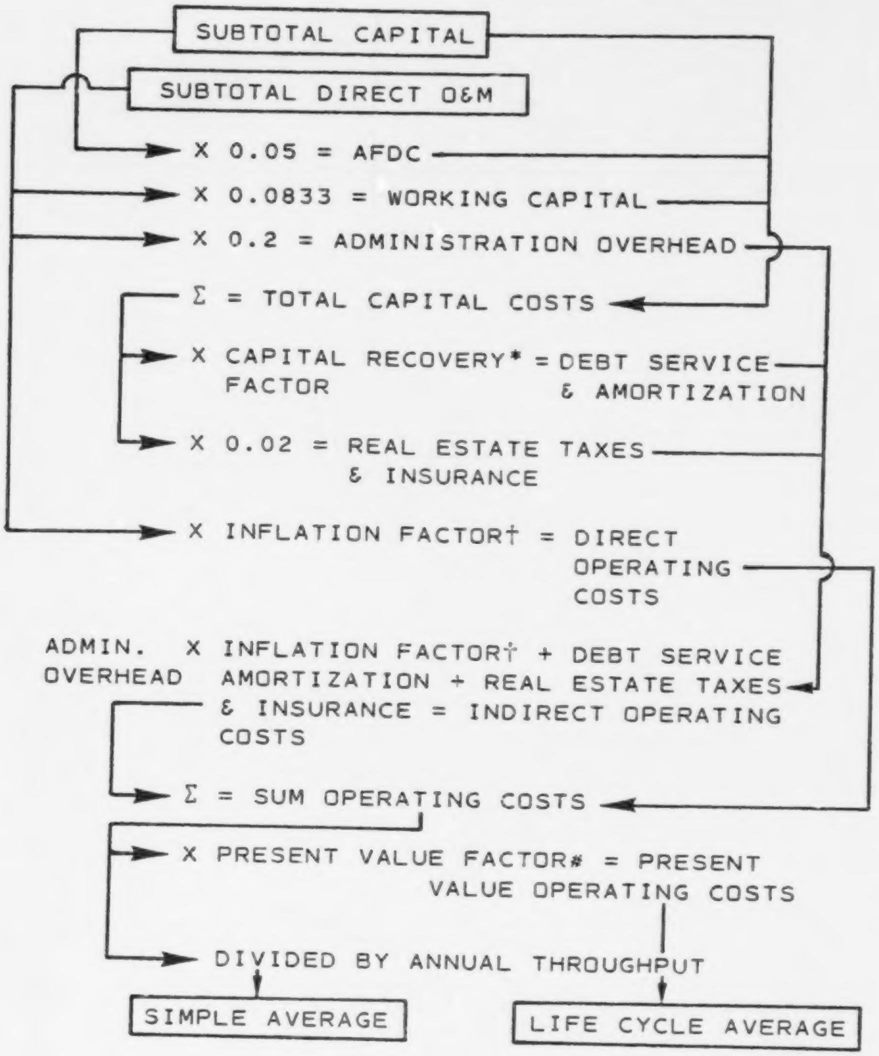
SUBTOTAL CAPITAL
SUBTOTAL DIRECT O&M
X 0.05 = AFDC
X 0.0833 = WORKING CAPITAL
X 0.2 = ADMINISTRATION OVERHEAD
Σ = TOTAL CAPITAL COSTS
X CAPITAL RECOVERY* FACTOR = DEBT SERVICE & AMORTIZATION
X 0.02 = REAL ESTATE TAXES & INSURANCE
X INFLATION FACTOR† = DIRECT OPERATING COSTS
ADMIN. OVERHEAD X INFLATION FACTOR† + DEBT SERVICE AMORTIZATION + REAL ESTATE TAXES & INSURANCE = INDIRECT OPERATING COSTS
Σ = SUM OPERATING COSTS
X PRESENT VALUE FACTOR# = PRESENT VALUE OPERATING COSTS
DIVIDED BY ANNUAL THROUGHPUT
SIMPLE AVERAGE
LIFE CYCLE AVERAGE

---

* $\frac{i(1+i)^n}{(1+i)^n - 1}$ i = INTEREST OR INFLATION RATE PER YEAR.

† $(1+i)^n$ n = NUMBER OF YEARS.

# $\frac{1}{(1+i)^n}$

Figure 9. Life cycle cost calculator.

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estimates represent a reasonable estimate of the costs for a facility and include:

For Capital Costs

- Cost of purchased equipment required for the modules including contingencies and contractor's profit
- Cost of equipment delivery (for Chicago), field erection, installation, piping, concrete, steel, instrumentation, electrical, insulation, and all appurtenances required for proper operation of the modules
- Prime contractor engineering for the technology
- Licenses and fees
- Construction overhead (included in AFDC)
- Costs of buildings, only where inherently required for proper module function or protection from weather
- Land costs (greater Chicago area)
- Working capital
- Allowance for funds during construction.

For O&M Costs

- Utility costs
- Labor
- Chemical costs (transported to site and prepared for use)
- Maintenance
- Product or residuals (salable commodities as well as further disposal costs)
- Administrative overhead
- Debt service and amortization
- Real estate taxes and insurance.

Costs which are ancillary to the analysis and not directly relevant to a specified module or technology-level functions are:

- The cost of specialized equipment modules not listed in Section 6 for each technology.
- The cost of structures, equipment, or other items or specialized services, supplies, etc., which are over and above those incorporated in typical applications.
- Salvage values - it is assumed that most structures and equipment usually deemed salvageable are rendered unsalvageable by the destructive and contaminating effects of hazardous waste constituents.

Table 9 is a form which can be used to list the user's particular technology configuration and tabulate the necessary cost information.

LIFE CYCLE COST COMPARISONS

The results of the life cycle cost and technology performance comparisons are the subject of Section 4 (Hazardous Waste Management Alternatives) of this report. Alternative treatment/disposal schemes for select waste streams are compared according to their annual life cycle cost averages according to scale; their performance meeting the hazardous waste treatment and disposal criteria as promulgated under the Resource Conservation and Recovery Act (PL-580).

There may, however, be instances where the user wishes to generate a life cycle cost estimate for purposes of comparing a newly configured technology with others or with those defined in Section 6. Such calculations are possible using the modular-specific cost data available therein. Where unit costs other than those for the Chicago example are desired, appropriate changes may be made in the Data in Appendices B and C. Module costs are then generated using the formulas in Appendix F.

A life cycle computation similar to that shown in Figure 9 may be compiled. Direct operation costs are calculated from the annual O&M costs. Indirect operating costs include administrative overhead, debt service and amortization, and real estate taxes and insurance.

The above calculation may be repeated for several scales of operation in order to obtain a plot of life cycle average costs versus major scaling factors.

TABLE 9. ESTIMATION OF INSTALLED CAPITAL, ANNUAL O&M, AND LIFE CYCLE COSTS

Technology ____________________

Date ____________________

Waste Description ____________________

Special Conditions ____________________

Capital Costs

MODULES	INSTALLED COST (mid-1978 $'s)	NOTES
	$	
	$	
	$	
	$	
	$	
	$	
	$	

1) TOTAL MODULES $ ____________________

Supplemental Capital Costs

DESCRIPTIONS	INSTALLED COST	NOTES
	$	
	$	
	$	

2) TOTAL SUPPLEMENTAL $ ____________________

3) SUBTOTAL CAPITAL COSTS (1+2) $ ____________________

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TABLE 9 (Continued)

O&M Costs

Input Flow Rate ______________

Modules Name	Labor (hrs/yr) Class 1	 Class 2	 Class 3	Annual Energy Reqd. (specify) Energy 1	 Energy 2	 Energy 3
______	______	______	______	______	______	______
______	______	______	______	______	______	______
______	______	______	______	______	______	______
______	______	______	______	______	______	______
______	______	______	______	______	______	______
______	______	______	______	______	______	______
______	______	______	______	______	______	______
______	______	______	______	______	______	______
______	______	______	______	______	______	______
Total	______	______	______	______	______	______
x $/unit	$______	$______	$______	$______	$______	$______
equals	______ (4)	______ (5)	______ (6)	______ (7)	______ (8)	______ (9)

10) Total Labor (4+5+6)$______________

11) Total Energy Required (7+8+9)$______________

O&M Costs

Modules Name	Annual Maint. Costs $	Annual Chemical Costs $	Other (specify) $
______	______	______	______
______	______	______	______
______	______	______	______
______	______	______	______

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TABLE 9 (continued)

O&M Costs (continued)

Modules Names	Annual Maint. Costs $	Annual Chemical Costs $	Other (specify) $
Total	$ (12)	$ (13)	$ (14)

15) Subtotal(10+11+12+13+14) $______________________________

Supplemental O&M Costs

Items	Annual Costs
16) Total	$

17) Subtotal Direct O&M Costs (15+16) $________________________

COMPUTATION OF

Subtotal Capital Costs = (3) $__________________________

18) Allowance for Funds During Construction
Subtotal Capital Costs (3) $ ______________________(0.05)

= $ ______________________

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TABLE 9 (continued)

19) Working Capital = (17) Subtotal Direct O&M Costs $ __________ x 0.0833

= $ __________

20) TOTAL CAPITAL COSTS = (3)+(18)+(19) = $ __________

TOTAL FIRST YEAR OPERATING COSTS

Subtotal Direct O&M Costs = (17) $ __________

21) Administrative Overhead =

Subtotal Direct O&M Costs (17) $ __________ x (0.02)

= $ __________

22) Debt Service and Amortization =

Total Capital Costs (2) $ __________

x Capital Recovery Factor* (   ) = $ __________

23) Real Estate Taxes & Insurance =

Total Capital Costs (2) $ __________ x (0.02)

= $ __________

24) TOTAL FIRST YEAR OPERATING COSTS = (17)+(21)+(22)+(23) = $__________

LIFE CYCLE AVERAGE COSTS

25) Direct Operating Costs =

Subtotal Direct O&M Costs (17) $ __________

x Inflation Factor† (____) = $ __________

26) Indirect Operating Costs =

Administrative Overhead (21) $ __________

x Inflation Factor† (____) = $ __________

Debt Service & Amortization (22) $ __________

Real Estate Taxes & Insurance (23) $ __________

= $ __________

27) Sum Annualized Costs = $ __________

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TABLE 9 (continued)

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28) Present Value Operating Costs =

Sum Annualized Costs (27) $ ______________________

x Present Value Factor#(____) = $ __________________

LIFE CYCLE AVERAGE COSTS = Present Value Operating Costs (28) $ __________

÷ Annual Throughput = $__________/__________

---

* $\frac{i(1 + i)^n}{(1+i)^n - 1}$

† $(1 + i)^n$

# $\frac{1}{(1 + i)^n}$

i = interest or inflation rate per year

n = number of years

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SECTION 6

DESCRIPTIONS AND COST DATA FOR HAZARDOUS WASTE TREATMENT AND DISPOSAL TECHNOLOGIES

This section includes technical descriptions and cost data for the 21 hazardous waste treatment/disposal technologies evaluated in this study. Each description includes the following engineering/design information:

- Technology description
    - modules
    - flow diagram
    - design details
- Any changes in technology configuration with scale
- Hazardous waste streams treated and/or disposed of according to industry and waste type.

Also included is the following cost information:

- Summary of capital costs
- Changes in capital costs with scale
- Summary of first year operating costs
- Changes in operation and maintenance (O&M) costs with scale
- Life cycle average costs
- Life cycle average costs according to scale.

Costs were computed at fixed scales of operation typical of waste discharge rates from the three industries studied (Table 2). Costs given are for mid-1978 and are based on unit costs as they apply in Chicago, Illinois.

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PRECIPITATION/FLOCCULATION/SEDIMENTATION

Description

Precipitation, flocculation and sedimentation are consecutive unit processes used for reacting, solidifying, and settling out various waste constitutents in the same stream (Figure 10). Precipitation transforms a substance in solution into an insoluble form resulting in a second phase, often in the form of small solid particles or colloids. Flocculation then transforms these solids into larger suspended particles so that they can be removed by gravity settling in a sedimentation basin.

Precipitation is a physicochemical process whereby waste constituents (often inorganic ions) are changed into a solid phase and thereby removed from solution. Precipitation involves an alteration of the chemical equilibrium relationships affecting the solubility of the component(s). This is most often accomplished through changes in pH, or by reacting the species with added chemical(s) and forming an insoluble product. Precipitation is achieved by adding and rapidly mixing the appropriate amount of chemicals with the incoming waste stream. Mixing is accomplished by a stirring device mounted on the mixing tank. Sufficient retention time (usually less than one minute) is required to assure complete chemical contact. Flocculating agents may also be added in the rapid-mix tank.

Flocculation defines the process by which the suspended particles generated by precipitation agglomerate into larger particles. Typically, this is achieved in a basin with gentle agitation provided by paddles or other stirring devices. Sufficient retention time is required to allow floc formation.

Once suspended particles have been flocculated into larger particles, they are removed from the liquid stream by sedimentation. This is done by retaining the waste flow in a quiescent basin. The particles suspended in a liquid (if they are sufficiently dense) settle by means of gravitational forces acting on the particles. Scraping devices (sludge collectors) in the basin travel along the bottom and deposit the settled solids into the sludge hopper. The solids are pumped to a sludge dewatering system and are prepared for recovery and/or disposal.

Changes in Configuration with Scale

Typically, additional units are added in parallel to treat larger flows. The models used for this analysis (Appendix F) assume that the maximum volume for the flash mixer is 1,000 ft^3. The flocculator module is expanded to accommodate additional paddle cells as necessary. Each paddle cell has a maximum volume of 3,600 ft^3. The maximum sedimentation basin depth is 10 ft.

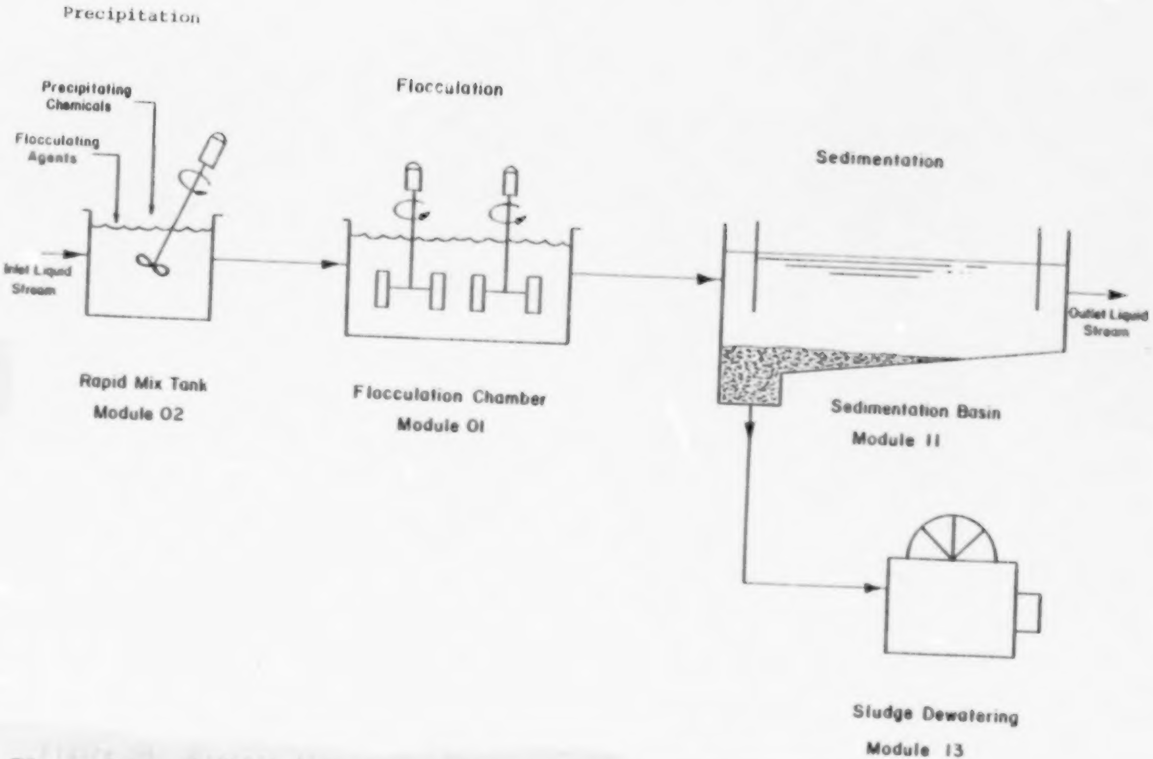
Precipitation
Precipitating Chemicals
Flocculating Agents
Inlet Liquid Stream
Rapid Mix Tank
Module 02
Flocculation
Flocculation Chamber
Module 01
Sedimentation
Outlet Liquid Stream
Sedimentation Basin
Module 11
Sludge Dewatering
Module 13

Figure 10. Process flow diagram for precipitation/flocculation/sedimentation.

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Applications

Precipitation/flocculation/sedimentation is commonly applied in the treatment of wastewater streams containing soluble heavy metals and colloidal hazardous substances. A summary of general wastewater treatment applications in the three industries is presented below:

Inorganic Chemicals Industry--
Many manufacturing processes within the inorganic chemicals industry produce wastewaters that contain suspended solids and soluble heavy metals. Examples are found in the manufacture of titanium dioxide and chromium pigments. Precipitation, flocculation and sedimentation are used to treat many of these wastewaters.

Metal Finishing Industry--
Soluble salts of copper, nickel, cadmium and chromium are removed from wastewater streams by precipitation as hydrated oxides, using lime followed by flocculation and sedimentation. Any chromium usually present as chromate or dichromate must first be reduced to the trivalent state so that the precipitation process will be effective.

Pesticides--
In the manufacture of certain pesticides (i.e., DDT and Toxaphene), sedimentation with flocculation is under consideration as a preliminary treatment step within a contemplated wastewater treatment scheme involving other steps.

Costs

Capital and first year operating costs are calculated for precipitation/flocculation/sedimentation (Tables 10 and 11). The most costly unit processes for the 1,000 gpm facility are the sedimentation basin and sludge dewatering. The sludge rate is assumed to be 100 gpm and precipitating chemical is added at a rate of 0.1 gpm. The concentration of total suspended solids in the raw waste is 100 ppm. The total capital cost for the Chicago-based example is $779,403. Major operating costs are labor, maintenance and chemical costs. The total first year operating costs are $260,685.

Figure 11 shows the total capital costs (excluding land costs) at five scales of operation for the technology. The accompanying graph shows the land area requirements at the same scales of operation. The slope of the capital cost curve in Figure 11 indicates that there are significant economies of scale in terms of initial costs for the range studies. For example, at 1,000 gpm, the estimated total capital cost (less land) is $5.82/1,000 gal; at 5,000 gpm, it is $3.71/1,000 gal

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TABLE 10. SUMMARY OF CAPITAL COSTS FOR PRECIPITATION/FLOCCULATION/SEDIMENTATION*

Capital Cost Category Module	Costs†						Quantities	
	Site Preparation	Structures	Mechanical Equipment	Electrical Equipment	Land	Total	Land (ft2)	Other Volume (gal)
Flash mixer	$ 29	$ 6,420	$ 2,810	$ 281	$ 286	---	384	---
Flocculator	66	7,150	5,040	0	654	---	880	---
Sedimentation basin	6,980	67,400	308,000	562	5,950	---	8,000	---
Sludge dewatering	36	8,520	184,000	1,840	823	---	1,110	---
Chemical storage	389	2,130	2,840	---	321	---	432	1,440
Chemical storage	1	20	19,432	---	1	---	10	---
Waste pump	---	---	2,950	---	---	---	---	---
Sludge pump	---	---	798	---	---	---	---	---
Yard piping	---	---	60	---	---	---	---	---
Chemical pump	225	---	1,130	---	---	---	---	---
Total	7,726	91,640	527,060	2,683	8,035		10,816	1,440
Supplemental capital costs	---	97,324#	---	---	---	---	---	---
Subtotal of capital costs	---	---	---	---	---	734,468	---	---
Working capital**	---	---	---	---	---	8,212	---	---
AFDC‡	---	---	---	---	---	36,723	---	---
Grand total of capital costs	---	---	---	---	---	779,403	---	---

* Scale = 1,000 gpm; TSS = 100 ppm; sludge wasting rate = 100 gpm; liquid chemical input = 0.1 gpm.

† Mid-1978 dollars.

Building.

** At one month of direct operating costs.

‡ Allowance for funds during construction at 5% of capital costs.

TABLE 11. SUMMARY OF FIRST YEAR O&M COSTS FOR PRECIPITATION/FLOCCULATION/SEDIMENTATION*

	Costs†							Quantities	
	Labor								
O&M Cost Category Module	Type 1 Operator 1 ($7.77/hr)	Type 2 Operator 2 ($9.19/hr)	Type 3 Laborer ($6.76/hr)	Energy Electrical ($0.035/KWH)	Maintenance Costs	Chemical Costs	Total	KWH (yr)	Other Chemicals (gal/yr)
Flash mixer	$ 63	$ 41	$ 2,552	$ 598	$ 225	---	---	17,086	---
Flocculator	79	46	1,440	1,300	252	---	---	37,143	---
Sedimentation basin	1,471	104	15,361	102	30,800	---	---	2,914	---
Chemical storage	12	14	184	---	398	$ 5,940	---	---	12,480
Chemical storage	6	12	180	---	400	400	---	---	---
Waste pump	---	---	---	1,730	---	---	---	49,429	---
Sludge pump	---	---	---	173	---	---	---	4,943	---
Yard piping	---	---	103	---	6	---	---	---	---
Chemical pump	---	---	---	17	---	---	---	486	---
Sludge dewatering	1,471	451	15,361	14,100	1,850	404	---	402,857	---
Total	3,102	668	35,181	18,020	33,931	6,294	---	514,858	12,480
Supplemental O&M costs	---	---	---	---	1,348	---	---	---	---
Subtotal of direct O&M costs	---	---	---	---	---	---	98,544	---	---
Administrative overhead#	---	---	---	---	---	---	19,709	---	---
Debt service and amortization**	---	---	---	---	---	---	126,844	---	---
Real estate taxes and insurance‡	---	---	---	---	---	---	15,588	---	---
Total first year operating costs	---	---	---	---	---	---	260,685	---	---

* TSS = 100 ppm; liquid chemical input = 0.1 gpm; 1,000 gpm.

† Mid-1978 dollars.

# At 20% of direct operating costs.

** At 10% interest over 10 years.

‡ At 2% of total capital.

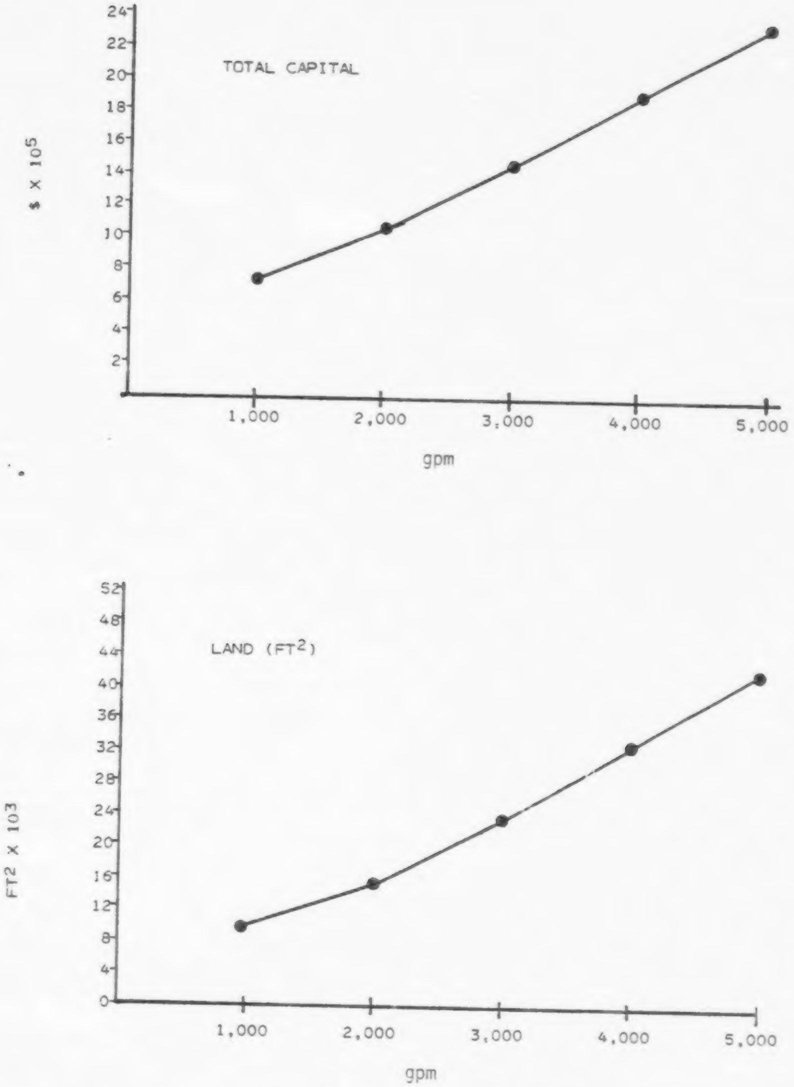

Figure 11. Precipitation/flocculation/sedimentation: changes in total capital costs with scale.

treated. This is due, in part, to the ability to expand capacity and use common basins, pumps, storage facilities and drive motors.

Figure 12 shows the changes in O&M requirements with scale for the needed facilities (operating 8 hr/day and 260 day/yr). Labor costs are largely attributable to the cost of skilled laborers required to oversee the process and perform certain duties (chemical addition, flow monitoring, etc.). The cost for supervisory personnel (Operator 1 and Operator 2) are fairly constant over the range of scales of operation. Maintenance costs increase with scale in a manner similar to total capital costs. At larger facilities, greater economies of scale are partially offset by the higher service demands placed on mechanical equipment, particularly the sludge collection system in the sedimentation basins. Electricity requirements per unit volume of waste decrease slightly at larger scales of operation (4.13 KWH/1,000 gal at 1,000 gpm and 3.87 KWH/1,000 gal at 5,000 gpm). Chemical costs demonstrate a negative economy of scale ($0.05 and $0.10 per 1,000 gal treated at 1,000 and 5,000 gpm, respectively). Increases in chemical demand are due to less efficient chemical contact in large scale facilities.

The average cost of the Chicago-based model facility over a life cycle of 10 years is calculated in Table 12 . The life cycle average cost is $1.72/1,000 gal ($0.45/m^3) for the 1,000 gpm facility. Figure 13 shows the variation in the average cost per unit volume with scale. The decrease in cost per unit volume with increased capacity reflects the economies of scale observed for total capital, maintenance and power costs.

MULTIMEDIA FILTRATION

Description

Multimedia filtration is commonly applied to aqueous hazardous wastes in order to remove solids prior to further treatment, to upgrade existing conventional plants, and is a common technology included in new advanced treatment facilities for polishing of effluents. It is also used in implementing technologies (e.g. carbon absorption, reverse osmosis or ultrafiltration). Next to gravity sedimentation it is the most widely used process for separation of wastewater solids (6).

The filter bed is typically contained within a basin or tank (Figures 14 and 15) and is supported by an underdrain system which allows the filtered liquid to be drawn off while retaining the filter media in place. The underdrain system typically consists of metal or plastic strainers located at intervals on the bottom of the filter. As suspended particle-laden wastes pass through the bed, particles are trapped on top of and within the media, thus reducing its porous nature and

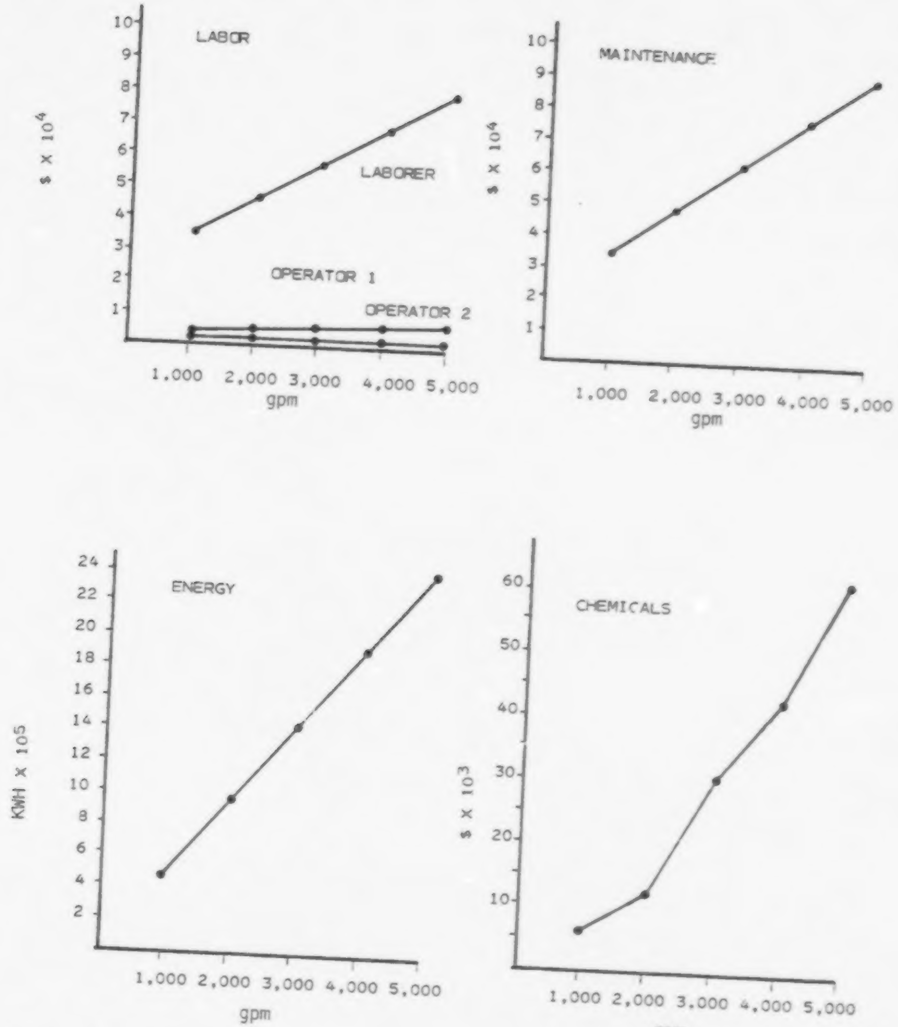

Figure 12. Precipitation/flocculation/sedimentation: changes in O&M requirements with scale.

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TABLE 12. COMPUTATION OF LIFE CYCLE AVERAGE COST FOR IMPLEMENTING PRECIPITATION/FLOCCULATION/SEDIMENTATION (LIFETIME - 10 YEARS)

Item	Direct Operating Costs*	Indirect Operating Costs†	Sum Operating Costs	Present Value Annualized Costs#	Annual Quantity of Throughput (x 1,000 Gal.)**
YEAR 1‡	98,544	162,141	260,685	260,685	124,800
YEAR 2	108,398	164,112	272,510	247,737	124,800
YEAR 3	119,238	166,280	285,518	235,966	124,800
YEAR 4	131,162	168,665	299,827	225,264	124,800
YEAR 5	144,278	171,288	315,566	215,536	124,800
YEAR 6	158,706	174,174	332,880	206,692	124,800
YEAR 7	174,577	177,348	351,924	198,652	124,800
YEAR 8	192,034	180,839	372,874	191,343	124,800
YEAR 9	211,238	184,680	395,918	184,699	124,800
YEAR 10	232,362	188,905	421,266	178,658	124,800
TOTALS			3,308,968	2,145,232	1,248,000
Simple Average (Per 1,000 Gal.)			2.65		
Simple Average (Per Cubic Meter)		0.70	0.70		
Life Cycle Average (Per 1,000 Gal.)				1.72	
Life Cycle Average (Per Cubic Meter)				0.45	0.45

---

* Assumes 10% annual inflation.

† Inflation increases the administrative overhead only.

# Assumes a 10% interest/discount rate to the beginning of the first year of operation.

** 1,000 GPM x 60 min x 8 hrs/day x 260 days/yr.

‡ First year costs in mid-1978 dollars - for Chicago example.

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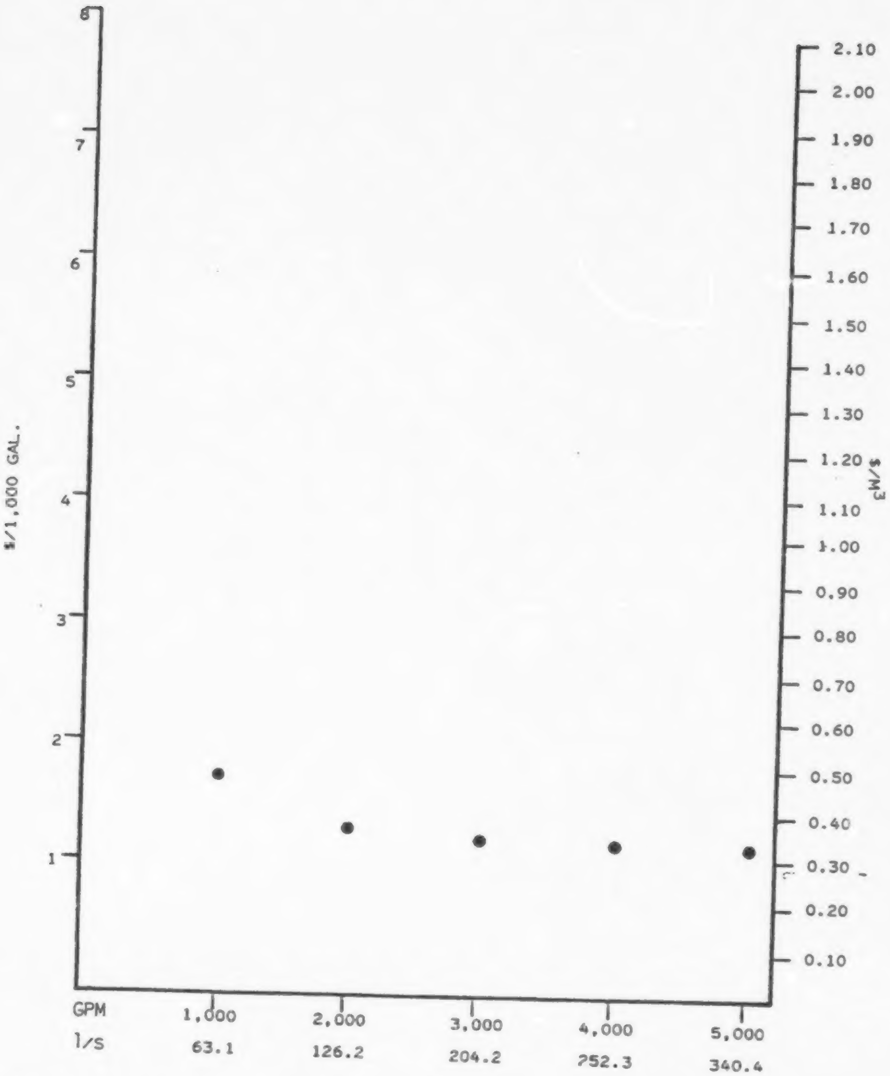

Figure 13. Precipitation/flocculation/sedimentation: life cycle costs at five scales of operation.

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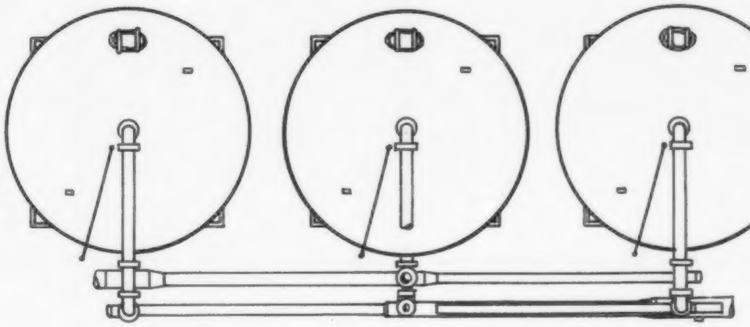
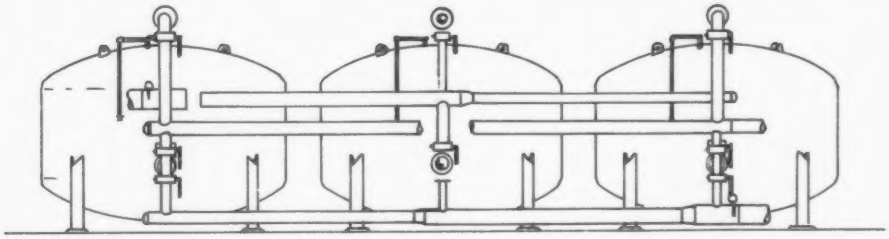


Plan View



Elevated View

Figure 14. Typical arrangements of vertical filter tanks.

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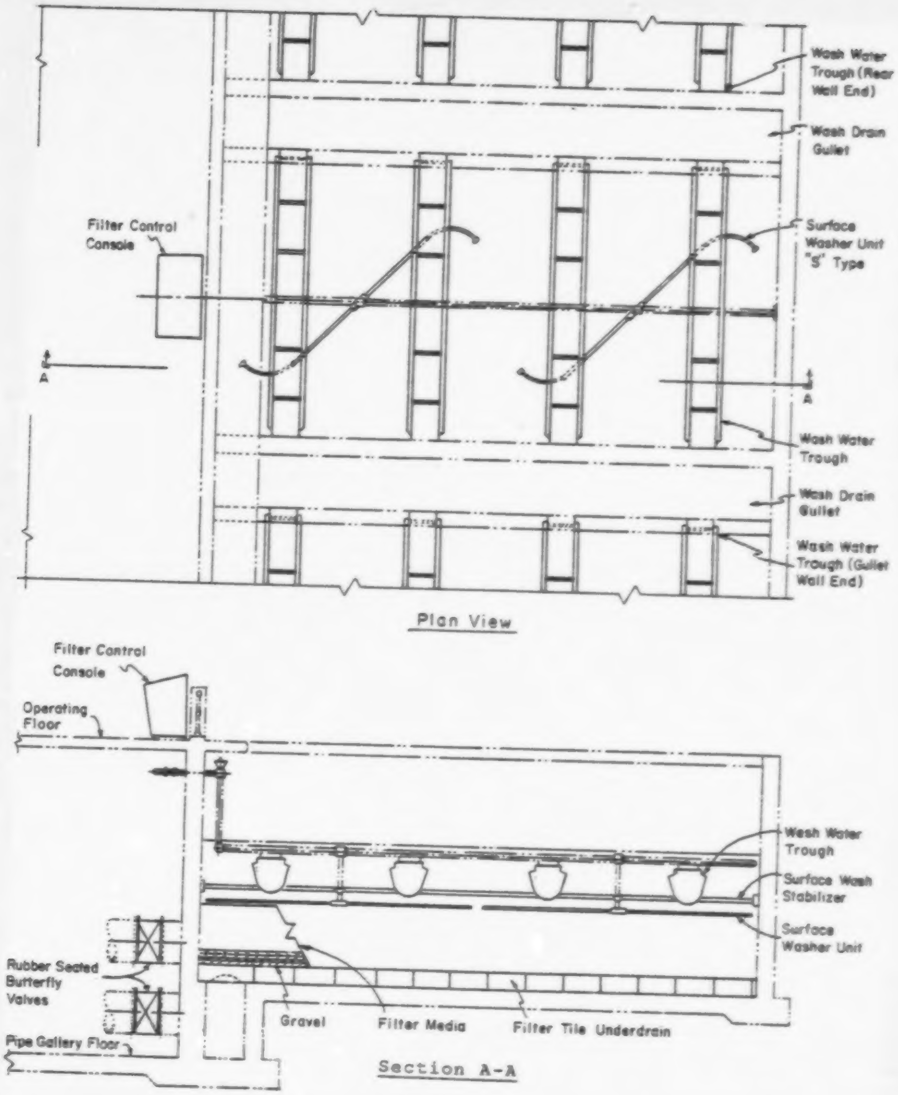

Wash Water Trough (Rear Wall End)
Wash Drain Gullet
Filter Control Console
Surface Washer Unit "S" Type
A
A
Wash Water Trough
Wash Drain Gullet
Wash Water Trough (Gullet Wall End)
Plan View
Filter Control Console
Operating Floor
Wash Water Trough
Surface Wash Stabilizer
Surface Washer Unit
Rubber Seated Butterfly Valves
Gravel
Filter Media
Filter Tile Underdrain
Pipe Gallery Floor
Section A-A

Figure 15. Arrangement of multi-media filtration basins.

either reducing the filtration rate at constant pressure or increasing the amount of pressure needed to force the water through the filter. If left to continue in this manner, the filter eventually plugs up with solids. The solids, therefore, must be removed. To do this, a washwater stream is forced through the bed of granular particles in the reverse direction of the original fluid flow. The washwater is sent through the bed at a velocity sufficiently high so that the filter bed becomes fluidized and turbulent. In this turbulent condition, the solids are dislodged from the granular particles and are discharged in the spent wash water. This whole process is referred to as "backwashing". When the backwashing cycle is completed, the filter is returned to service. The spent backwash water contains the suspended solids removed from the liquid and is pumped to a dewatering process in order to produce a manageable sludge.

Changes in Configuration with Scale

Filter surface areas (cross sectional) up to 1,000 ft^2 are provided by one or more vertical filter tanks, as shown in Figure 14. For larger surface area, concrete basins (Figure 15) are used. The total surface area of the filter bed(s) is calculated as influent flow rate (gpm) divided by 5.0.

Applications

Multimedia filtration is applied in mumerous municipal and industrial cases where hazardous wastes are generated. Applicability to specific hazardous waste constituents is difficult to ascertain since the purpose of filtration is solids removal rather than treatment of specific compounds. The following general applications are observed:

- Removal of residual biological floc in settled effluents from secondary treatment by trickling filters or activated sludge processes used for treating organic hazardous wastes

- Removal of solids remaining after the chemical coagulation of wastewaters in physical/chemical waste treatment
  (Primarily metals and non-metal inorganics)

- Removal of solids prior to ultrafiltration, reverse osmosis, distillation or other treatment technologies which can be hampered by appreciable solids in the influent waste.

Costs

Summaries of capital and first year operating costs for multimedia filtration are shown in Tables 13 and 14. These estimates are based on mid-1978 costs for components, unit processes, labor, utilities, etc., as applicable in Chicago, Illinois. The estimates are based on the cost files in Appendices B and C, and the cost equations described in Appendix F.

As shown in Table 13, the most costly unit processes are the filters and the sludge dewatering. At the scale of operation (5,000 gpm) shown in the example calculations, concrete basins instead of metal tanks are used to contain the filter bed. This is reflected in the structures cost for the filter. The total capital cost for a 5,000 gpm facility (included working capital and allowance for funds during construction) is $1,086,222. The highest operating cost for multimedia filtration is sludge dewatering power requirements (almost 80 percent of the direct O&M). Total labor costs for the large facility are $83,355/yr for the crew of laborers and operators. Sludge dewatering represents a large portion of both the capital and annual operating costs. Substantial savings can, therefore, be achieved by using alternative backwash/dewatering methods, such as settling or evaporation ponds for large scale operations.

Figure 16 shows the capital costs (exclusive of land costs) for five scales of operation and the accompanying land area requirements. The total capital cost (less land costs) for a 1,000 gpm facility is $270,088 which is equivalent to a cost of $2.16/1,000 gallons. This compares to $1.57 at a scale of 5,000 gpm and indicates economies of scale exist for the capital investment. This is due, in part, to higher costs for tank installations versus the basins which are used above 1,000 gpm.

The O&M requirements for multimedia filtration as a function of scale are shown in Figure 17. Energy requirements (primarily for sludge dewatering) decrease significantly below 5,000 gpm. Maintenance costs (per 1,000 gal of waste treated) are $0.05 at 1,000 gpm; increase to $0.12 at 2,000 gpm, and then decrease to $0.09 at 5,000 gpm. Chemical costs for filtration are minimal ($701 at 5,000 gpm) and are for water and sludge conditioning chemicals.

The average cost of the example facility over a life cycle of 10 years is calculated in detail in Table 15. The average cost for the 5,000 gpm facility is $1.54/1,000 gal ($0.41/m^3). Figure 18 shows the variation in the average cost (per unit volume) with scale. All O&M and life cycle estimates are based on an operating time of 8 hr/day and 260 day/yr. Capital and O&M costs are for the Chicago-based example in mid-1978 dollars.

TABLE 13. SUMMARY OF CAPITAL COSTS FOR MULTIMEDIA FILTRATION*

Capital Cost Category Module	Costs†							Quantities
	Site Preparation	Structures	Mechanical Equipment	Electrical Equipment	Land	Other Media	Total	Other Land (ft^2)
Multimedia Filter	$3,085	$104,500	$425,542	---	$1,530	$21,430	---	$2,050
Water Storage	389	2,130	2,840	---	321	---	---	432
Sludge Dewatering	33	7,970	178,000	$1,780	770	---	---	1,030
Waste Pump	---	---	10,800	---	---	---	---	---
Backwash Pump	---	---	2,950	---	---	---	---	---
Sludge Pump	---	---	798	---	---	---	---	---
Yard Piping	1,125	---	72,500	---	---	---	---	---
Total	4,632	114,600	693,430	1,780	2,621	21,430	---	3,512
Supplemental capital costs	---	141,303#	---	---	---	---	---	---
Subtotal of capital costs	---	---	---	---	---	---	$979,796	---
Working capital**	---	---	---	---	---	---	57,436	---
AFDC‡	---	---	---	---	---	---	48,990	---
Grand total of capital costs	---	---	---	---	---	---	1,086,222	---

* Scale = 5,000 gpm.

† Mid-1978 dollars.

# Building.

** At one month of direct operating costs.

‡ Allowance for funds during construction at 5% of capital costs.

TABLE 14. SUMMARY OF FIRST YEAR O&M COSTS FOR MULTIMEDIA FILTRATION*

O&M Cost Category Module	Costs† Labor Type 1 Operator 1 ($7.77/hr)	Type 2 Operator 2 ($9.19/hr)	Type 3 Laborer ($6.76/hr)	Energy Electrical ($0.035/KWH)	Maintenance Costs	Chemical Costs	Total	Quantities Other KWHs/yr
MM filter	$ 1,178	$ 5,278	$ 49,872	$ ---	$ 54,261	$ ---	$ ---	---
Water storage	---	---	---	---	398	324	---	---
Sludge dewatering	2,282	701	23,840	536,000	1,850	377	---	1.53 x 10^7
Waste pump	---	---	---	8,630	---	---	---	246,571
Dewatering pump	---	---	---	1,730	---	---	---	49,429
Sludge pump	---	---	---	173	---	---	---	4,943
Yard piping	---	---	204	---	363	---	---	---
Total	3,460	5,979	73,916	546,533	56,872	701	---	1.56 x 10^7
Supplemental O&M costs	---	---	---	---	1,770	---	---	---
Subtotal of direct O&M costs	---	---	---	---	---	---	689,231	---
Administrative overhead#	---	---	---	---	---	---	137,846	---
Debt service and amortization**	---	---	---	---	---	---	176,778	---
Real estate taxes and insurance‡	---	---	---	---	---	---	21,724	---
Total first year operating costs	---	---	---	---	---	---	1,025,579	---

* Scale = 5,000 gpm.

† Mid-1978 dollars.

# At 20% of direct operating costs.

** At 10% interest over 10 years.

‡ At 2% of total capital.

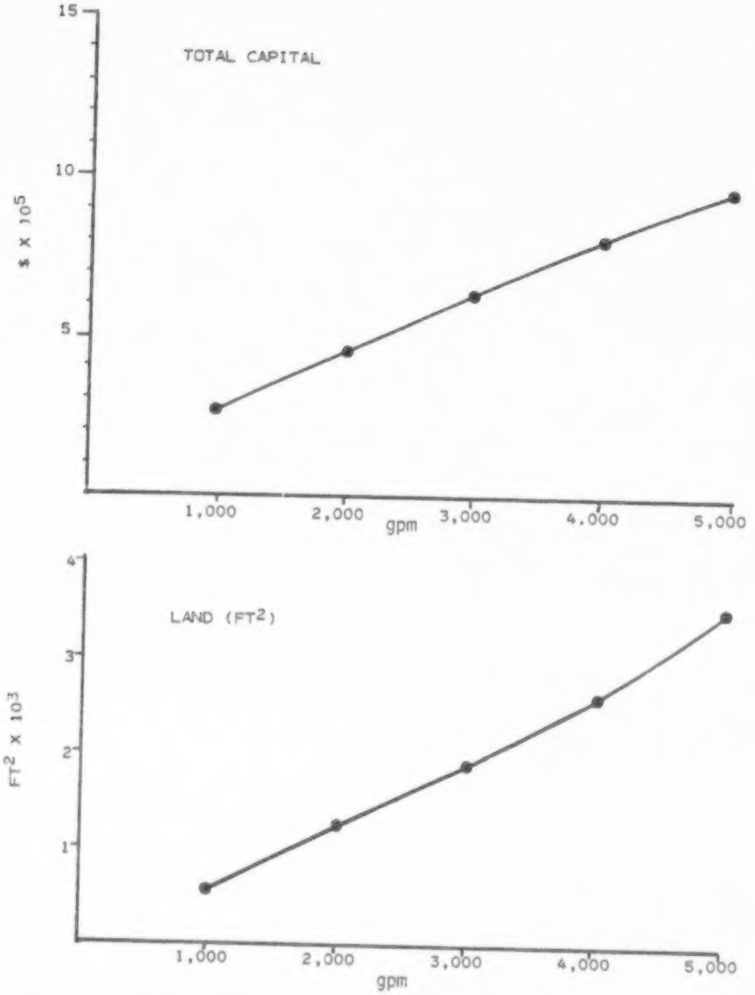


Figure 16. Filtration: changes in total capital costs with scale.

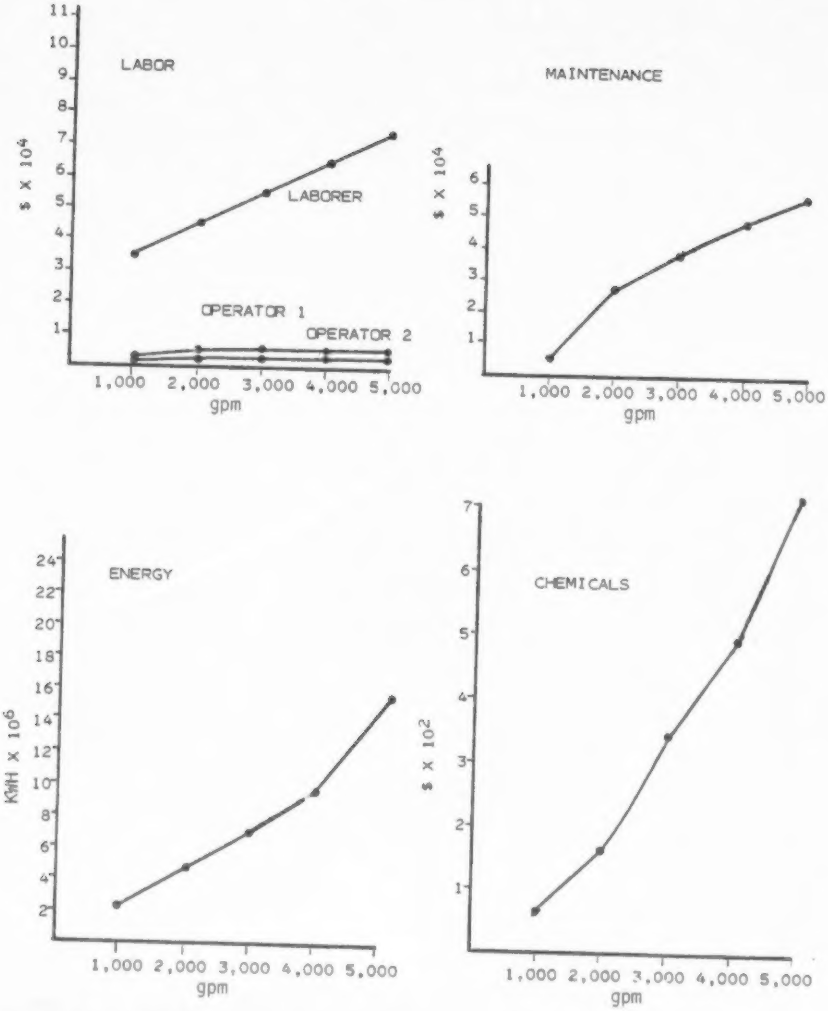


Figure 17. Filtration: changes in O&M requirements with scale.

TABLE 15. COMPUTATION OF LIFE CYCLE AVERAGE COST FOR IMPLEMENTING FILTRATION (LIFETIME - 10 YEARS)

Item	Direct Operating Costs*	Indirect Operating Costs†	Sum Operating Costs	Present Value Annualized Costs#	Annual Quantity of Throughput (x 1,000 Gal.)**
YEAR 1‡	689,231	336,348	1,025,579	1,025,579	624,000
YEAR 2	758,154	350,133	1,108,287	1,007,534	624,000
YEAR 3	833,970	365,296	1,199,265	991,128	624,000
YEAR 4	917,366	381,975	1,299,342	976,215	624,000
YEAR 5	1,009,103	400,323	1,409,426	962,657	624,000
YEAR 6	1,110,013	420,505	1,530,518	950,331	624,000
YEAR 7	1,221,015	442,705	1,663,720	939,126	624,000
YEAR 8	1,343,116	467,125	1,810,241	928,940	624,000
YEAR 9	1,477,428	493,988	1,971,415	919,680	624,000
YEAR 10	1,625,171	532,536	2,148,707	911,261	624,000
TOTALS			15,166,500	9,612,451	6,240,000
Simple Average (Per 1,000 Gal.)			2.43		
Simple Average (Per Cubic Meter)			0.64		
Life Cycle Average (Per 1,000 Gal.)				1.54	
Life Cycle Average (Per Cubic Meter)				0.41	

---

* Assumes 10% annual inflation.

† Inflation increases the administrative overhead only.

# Assumes a 10% interest/discount rate to the beginning of the first year of operation.

** 5,000 GPM x 60 min x 8 hrs/day x 260 days/yr.

‡ First year costs in mid-1978 dollars - for Chicago example.

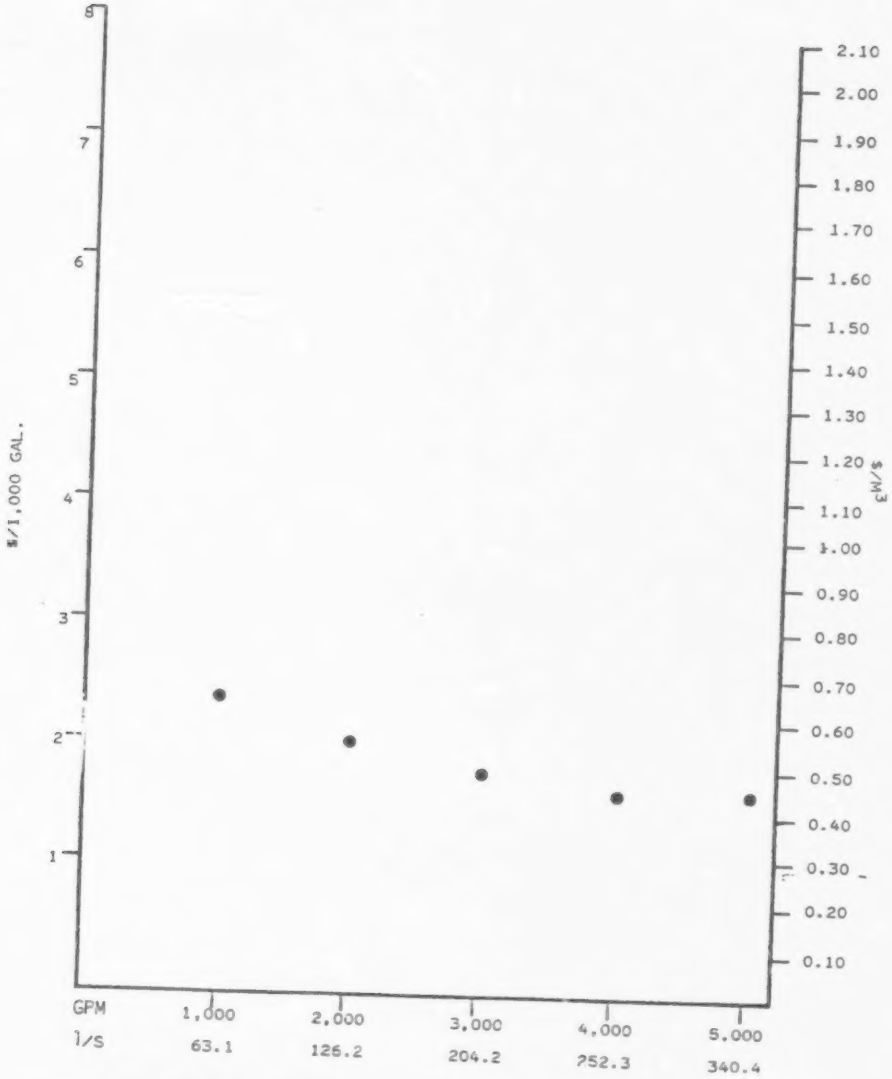


Figure 18. Filtration: life cycle costs at five scales of operation.

EVAPORATION

Description

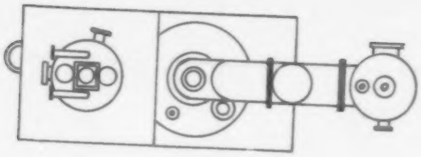
Evaporation is the vaporization of a liquid (often water) from a solution or a slurry for removal of the volatile liquid and concentration of non-volatile dissolved or suspended solids or liquids. The process and the equipment are similar to that of the stills or reboilers of distillation, except that in evaporation, no attempt is made to separate components of the vapor. As shown in Figure 19, the evaporation technology includes the evaporator unit, external separator and a condensor. The waste is introduced at the product inlet, vaporized and passed into the separator. The volatile component is captured in the condensor and the concentrated non-volatile component is removed at the product discharge. Evaporation pond, a separate technology is discussed in a subsequent section of this report.

Most present day evaporators are heated by steam contacting on metal tubes containing the material to be evaporated. Usually, the steam is at low pressure (i.e., below 40 lb force/in^2 absolute). Often the boiling liquid is under a moderate vacuum (down to 28 in. Hg). Reducing the boiling temperature of a liquid (by reducing pressure) increases the temperature difference between the steam and the boiling liquid and thereby increases the heat transfer rate in the evaporator.

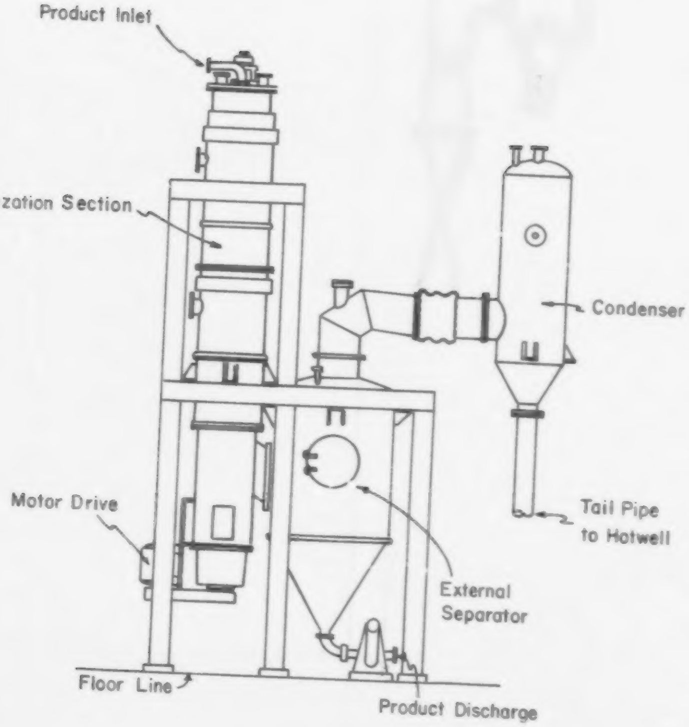
Changes in Configuration with Scale

The principal purpose of multiple-effect evaporation (Figure 20) is to minimize energy consumption. Most such evaporators operate on a continuous basis, although for a few difficult feeds, a continuous batch cycle may be employed. In a multiple-effect evaporator, steam from an outside source is condensed in the heating element of the first effect. If the feed to the first effect is at a temperature near the boiling point of the liquid in the first effect, 1 lb of steam will evaporate almost 1 lb of water. If the vapor produced in the first effect is the heating medium of the second effect (which is operating at a lower pressure than the first effect), almost another pound of water can be evaporated in the second effect. The resulting vapor could go to a condenser if the evaporator is a double-effect system, but if the evaporator is a triple-effect system the vapor may be used as the heating medium of the third effect. This process may be repeated for a number of effects. Each consecutive effect operates at a lower pressure than the preceding effect.

Large evaporators with up to 10 effects are common. The steam economy of a multiple-effect evaporator will increase in proportion to the number of effects, but it is usually somewhat smaller, numerically, than the number of effects, depending on



Plan View


Product Inlet
Vaporization Section
Condenser
Motor Drive
Tail Pipe to Hotwell
External Separator
Floor Line
Product Discharge

Elevated View

Figure 19. Detail of single evaporator showing associated equipment included in the evaporator module.

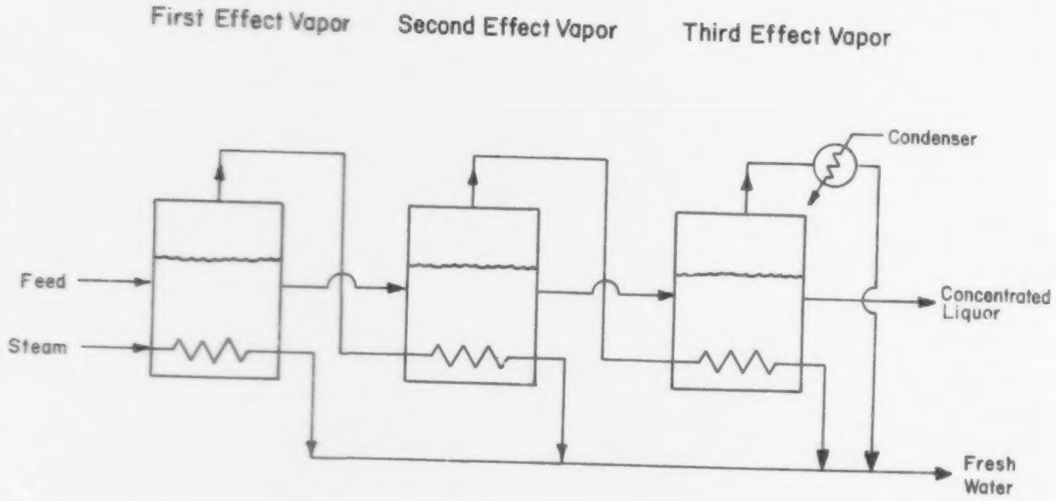

First Effect Vapor
Second Effect Vapor
Third Effect Vapor
Condenser
Feed
Steam
Concentrated Liquor
Fresh Water

Figure 20. Multiple effect evaporator with forward feed.

the boiling point elevation with concentration.

Applications

Inorganic wastes treated by evaporation include heavy metals, fluorides, chlorides, chlor-alkali production wastes, sulfur sludges and hydrochloric acids.

Organic wastes so treated include:

- Aliphatic hydrocarbons
- Amines
- Oxygenated hydrocarbons
- Phosphorus-containing organics
- Lead containing organics
- Metal organics
- Waste solvents
- Trinitrotoluene wastes (for disposal by incineration)
- "Black liquids" in paper production receivery systems.

Costs

Capital costs for evaporation are itemized in Table 16. The most costly elements, by an order of magnitude, are the evaporator (including the external separator) and the steam generator. At the operating scale of 1,000 gpm, it is estimated that 40,000 lb/hr of steam are required. The total capital cost for the facility is $602,397.

Table 17 summarizes the first year operating costs. Ninety percent of these costs are attributable to the energy, water and chemical requirements for the steam source. The total first year operating cost, including administrative overhead ($152,676), debt service and amortization ($158,911), and real estate taxes and insurance ($12,048) is $1,087,015.

Figure 21 shows the capital costs (excluding land costs) for five scales of operation and the corresponding land requirements for evaporation. The capital cost for the 1,000 gpm facility is equal to $4.10/1,000 gal treated (assuming 8 hr/day, 260 day/yr operation). This compares with a cost of $3.23/1,000 gal at the 5,000 gpm scale of operation. The capital cost data indicate significant economics of scale for the initial capital investment in evaporation.

The O&M requirements for evaporation as a function of scale are shown in Figure 22. Total labor costs are $65,709/yr at 1,000 gpm and $130,996/yr at 5,000 gpm. Maintenance costs also demonstrate significant economies of scale. Although energy requirements appear to increase exponentially with increased scale, economies of scale are retained by the efficiency of

TABLE 16. SUMMARY OF CAPITAL COSTS FOR EVAPORATION*

Capital Cost Category Module	Costs†						Quantities	
	Site Preparation	Structures	Mechanical Equipment	Electrical Equipment	Land	Total	Land (ft^2)	Other Volume (gal)
Evaporator	$ 410	$ 31,100	$ 216,250	$ 10,813	$ 1,370	---	1,840	---
Steam generator	38	1,865	148,500	---	353	---	475	40,000
Waste pump	---	---	2,950	---	---	---	---	---
Sludge pump	---	---	798	---	---	---	---	---
Yard piping	225	---	1,130	---	---	---	---	---
Total	673	32,965	369,628	10,813	1,723	---	2,315	40,000
Supplemental capital costs	---	97,324#	---	---	---	---	---	---
Subtotal of capital costs	---	---	---	---	---	$ 513,126	---	---
Working capital**	---	---	---	---	---	63,615	---	---
AFDC‡	---	---	---	---	---	25,656	---	---
Grand total of capital costs	---	---	---	---	---	602,397	---	---

* Scale = 1,000 gpm.

† Mid-1978 dollars.

Building.

** At one month of direct operating costs.

‡ Allowance for funds during construction at 5% of capital costs.

TABLE 17. SUMMARY OF FIRST YEAR O&M COSTS FOR EVAPORATION*

	Costs†							Quantities	
	Labor								
O&M Cost Category Module	Type 1 Operator 1 ($7.77/hr)	Type 2 Operator 2 ($9.19/hr)	Type 3 Laborer ($6.76/hr)	Energy Electrical ($0.035/KWH)	Maintenance Costs	Chemical Costs	Total	KWH (yr)	Other Natural gas (ft^3/yr)
Evaporator	$ 17,703	$ 10,476	$ 20,513	$ ---	$ 1,125	$ ---	--	--	---
Steam generator	1,179	209	15,586	319,000	1,807	372,000	--	--	44,120
Waste pump	--	---	---	1,730	---	---	--	49,429	---
Sludge pump	--	---	---	173	---	---	--	4,943	---
Yard piping	--	---	103	---	6	---	--	--	---
Total	18,882	10,685	36,202	320,903	2,938	372,000	--	54,372	44,120
Supplemental O&M costs	--	---	---	---	1,770	---	--	--	---
Subtotal of direct O&M costs	--	---	---	---	---	---	$ 763,380	--	---
Administrative overhead#	--	---	---	---	---	---	152,676	--	---
Debt service and amortization**	--	---	---	---	---	---	158,911	--	---
Real estate taxes and insurance ‡	--	---	---	---	---	---	12,048	--	---
Total first year operating costs	--	---	---	---	---	---	1,087,015	--	---

* Scale = 1,000 gpm.
† Mid-1978 dollars.
# At 20% of direct operating costs.
**At 10% interest over years.
‡ At 2% of total capital.

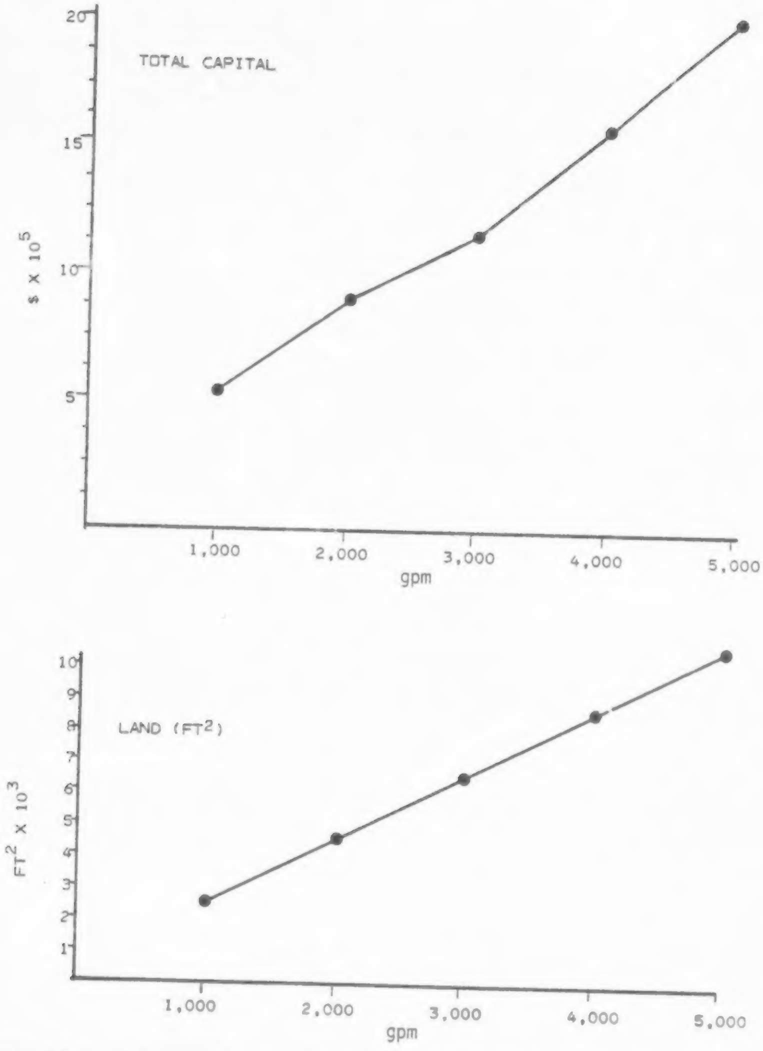


Figure 21. Evaporation: changes in total capital costs with scale.

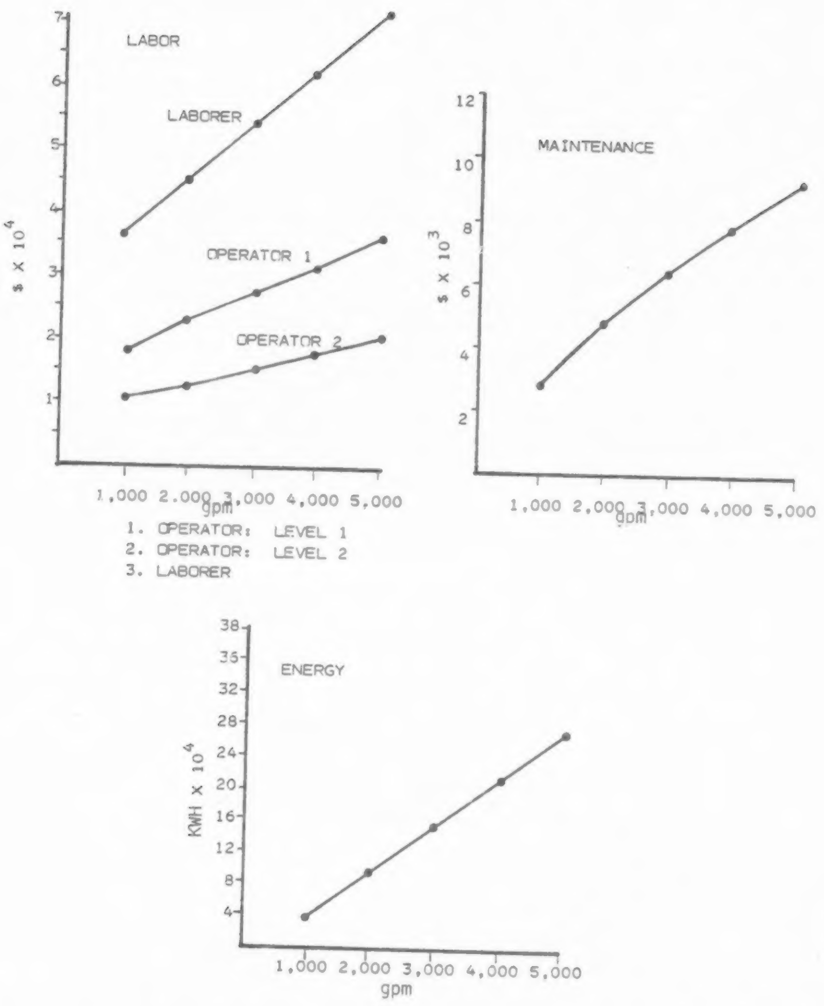


Figure 22. Evaporation: changes in O&M requirements with scale.

multiple effect systems. At all five scales of operation, 0.44 KWH are expended per 1,000 gal treated.

The average cost of the example facility over a life cycle of 5 years is calculated in Table 18. The life cycle average cost for the 1,000 gpm facility is $8.48/1,000 gal ($2.24/m^3). Figure 23 shows the variation in the average cost (per 1,000 gal) with scale. Significant economies of scale as observed for the capital and O&M costs are reflected in the life cycle average costs ($8.48/1,000 gal at 1,000 gpm vs. $7.30/1,000 gal at 5,000 gpm).

DISTILLATION

Description

Distillation is the boiling of a liquid solution and condensation of vapor for the purpose of separating the components.

In the distillation process there are two phases--the liquid and the vapor phase. The components to be separated by distillation are present in both phases, but in different concentrations. If there are only two components in the liquid, one concentrates in the condensed vapor (condensate), and the other in the residual liquid. If there are more than two components, the less volatile components concentrate in the residual liquid and the more volatile in the vapor or vapor condensate.

The waste is continuously fed into the distillation column (Figure 24) where it is cycled through the reboiler and heated by steam flowing through coiled tubes. Vaporized components return to the distillation columns for separation and the less volatile residual liquids or tars (bottoms product) are removed from the system for reuse or disposal. In fractional distillation, the vapors pass up through the column and are partitioned, according to their relative volatilities, throughout the sieve and valve tray packings. The vapors are drawn off, condensed, and stored in the accumulator. From the accumulator, a portion of the isolated fraction is returned to the column for refluxing, and the remainder is collected (overhead product) for reuse or disposal.

Changes in Configuration with Scale

Distillation column capacity requirements depend on the waste input rate and the volatilities of the constituents to be separated. The column must be large enough in diameter to (1) handle vapor flow without excessive pressure drop or entrainment; (2) handle liquid flow without excessive backup or hydraulic gradient (or crossflow); and (3) provide the contact time for the needed exchange of components between the liquid and vapor phases. For plate columns, the contacting height is based on

TABLE 18. COMPUTATION OF LIFE CYCLE AVERAGE COST FOR IMPLEMENTING EVAPORATION (LIFETIME - 5 YEARS)

Item	Direct Operating Costs*	Indirect Operating Costs†	Sum Operating Costs	Present Value Annualized Costs#	Annual Quantity of Throughput (x 1,000 Gal.)**
YEAR 1‡	$ 763,380	$323,635	$1,087,015	$1,087,015	124,800
YEAR 2	839,718	338,902	1,178,620	1,071,473	124,800
YEAR 3	923,690	355,697	1,279,387	1,057,344	124,800
YEAR 4	1,016,059	374,171	1,390,229	1,044,500	124,800
YEAR 5	1,117,665	394,492	1,512,156	1,032,823	124,800
TOTALS			6,447,407	5,293,155	624,000
Simple Average (Per 1,000 Gal.)			$ 10.33		
Simple Average (Per Cubic Meter)			$ 2.73		
Life Cycle Average (Per 1,000 Gal.)				$ 8.48	
Life Cycle Average (Per Cubic Meter)				$ 2.24	

---

* Assumes 10% annual inflation.

† Inflation increases the administrative overhead only.

# Assumes a 10% interest/discount rate to the beginning of the first year of operation.

** 1,000 GPM x 60 min x 8 hrs/day x 260 days/yr.

‡ First year costs in mid-1978 dollars - for Chicago example.

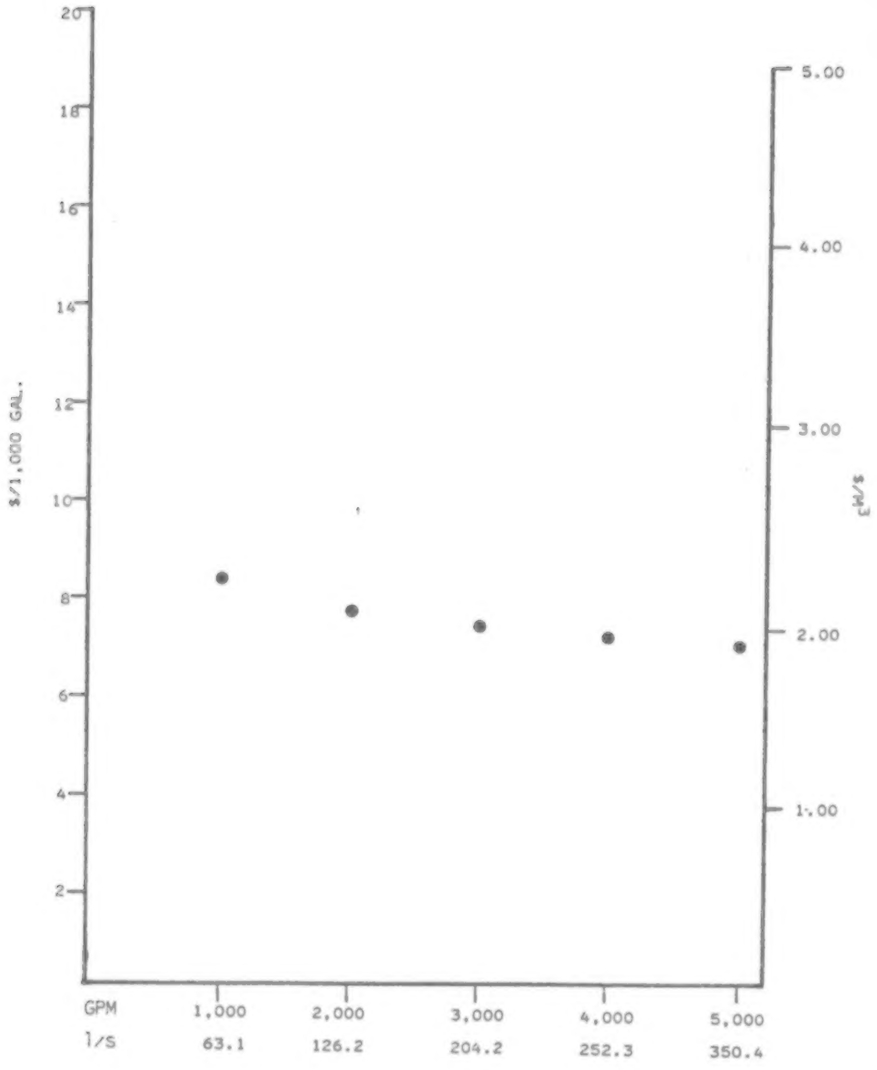


Figure 23. Evaporation: life cycle costs at five scales of operation.

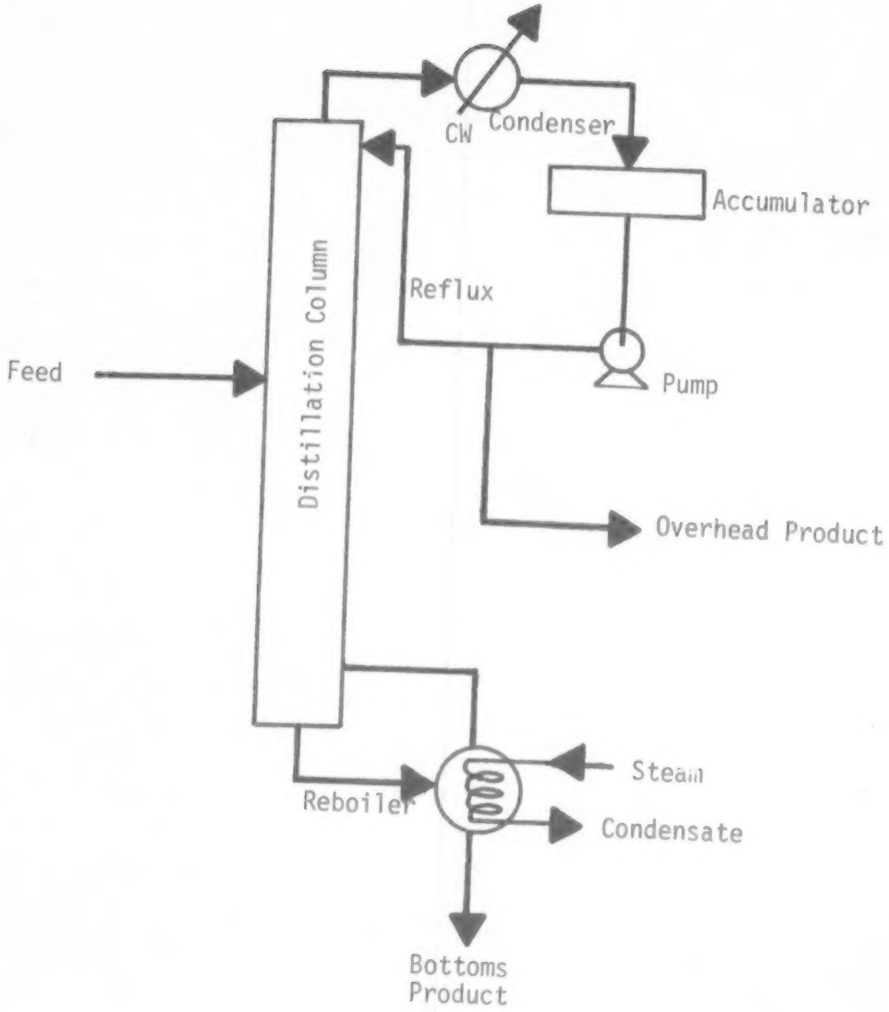

CW
Condenser
Accumulator
Reflux
Distillation Column
Feed
Pump
Overhead Product
Steam
Reboiler
Condensate
Bottoms Product

Figure 24. Continuous fractional distillation column.

the number of plates and the specified spacing between plates. Packed column height is estimated from the HTU (height of a transfer unit) that the packing type is rated for. Descriptions of the method for calculating column diameter and height is available in the literature (7-11). If the maximum diameter and height cannot accommodate the liquid flow, two or more equal sized columns are used to treat the waste.

In actual systems, there are many possible combinations of reflex ratio, column pressure, column height, column diameter and contacting internals. Useful data for economic evaluation of specific facilities is available (7-11). The general case presented here assumes single support processes (condensor, reboiler, accumulator, etc.) sized to accommodate the total flow rate (see cost/performance equations, Appendix F).

Applications

Distillation is an important treatment/recovery process for certain organic liquids, the products are contaminated with undesirable components or combinations of organic chemicals and byproducts. To separate the desirable products or fractionate the chemical from its secondary or waste byproducts, distillation is employed. This can either be a single operation or part of a treatment sequence.

Some additional typical applications include:

- Rerefining of contaminated fuel and waste oils
- Removal of unreacted cresols in the manufacture of TCP
- Chlorobenzene separation
- Recovery of acetone from an acetone/water waste stream
- Other solvent recoveries.

Materials that cannot generally be treated by distillation are organic peroxides or pyrophoric organics and inorganic wastes because of their explosive or non-volatile characteristics. There are no known treatment applications of distillation to waste pesticides. If waste streams that contain tars, etc., must be treated by distillation, the streams should receive preliminary treatment, if possible, to remove these materials, as they may tend to severely foul the equipment. If this is not possible, then special equipment may be required. Evaporators may be used before distillation to concentrate organic fractions (6).

Costs

The capital and O&M unit cost files (Appendices B and C) are used together with the cost equations in Appendix F to derive capital and first year operating costs for distillation (Tables 19 and 20). All costs are adjusted for inflation to mid-1978 values and are based on charges as they exist in the City of Chicago, Illinois.

The breakdown of costs for distillation is similar to that for evaporation; the most costly elements are the steam generator and distillation column. The major O&M costs are assorted with the steam generator in terms of power, fuel, water and chemicals. The total capital and first year operating costs are $1,037,415 and $1,674,328 respectively for the 1,000 gpm facility (this compares to $602,397 and $1,087,015 for an evaporation facility of the same capacity).

The change in the total capital costs (exclusive of land cost) according to the scale of operation is shown in Figure 25. Within the range of 2,000 to 5,000 gpm, distillation did not demonstrate any appreciable economies of scale. There is a marked increase in costs from 1,000 to 2,000 gpm though ($6.54/1,000 gal. vs. $7.00/1,000 gal. at 8,000 gpm). The reason for this is the increased capital costs for steam generation equipment and distribution to multiple columns at larger scales of operation.

Distillation O&M requirements are shown in Figure 26. Labor costs demonstrate significant economies of scale while maintenance, energy and chemical costs are constant throughout the range.

The direct and indirect operating costs (including debt service and amortization) are used to calculate the average cost over the 5-year life cycle of the example 1,000 gpm distillation facility. The life cycle average cost is $13.02/1,000 gal ($3.44/m^3). This compares to $8.48/1,000 gal. ($2.24/m^3) for evaporation. Figure 27 shows how the life cycle average costs (expressed as $/1,000 gal.) decrease with increased scales of operation up to 3,000 gpm. This decrease is attributed to the scales of economy observed for labor and chemical costs. However, at larger scales of operation (> 3,000 gpm), the increased capital and energy costs reduce these savings.

DISSOLVED AIR FLOTATION

Description

Dissolved air flotation is commonly used to concentrate and remove biological flocs from aerobic treatment systems. In

TABLE 19. SUMMARY OF CAPITAL COSTS FOR DISTILLATION*

Capital Cost Category Module	Costs†						Quantities	
	Site Preparation	Structures	Mechanical Equipment	Electrical Equipment	Land	Total	Land (ft^2)	Other Steam lbs/hr
Steam generator	$ 70	$ 6,490	$ 414,400	$ ---	$ 697	$ ---	937	120,000
Distillation column	120	4,540	232,730	11,637	768	---	1,032	---
Accumulator	389	2,130	2,840	---	321	---	432	---
Waste pump	---	---	2,950	---	---	---	---	---
Piping	675	---	39,300	---	---	---	---	---
Total	1,254	13,160	692,220	11,637	1,786	---	2,401	120,000
Supplemental capital costs	---	97,323#	---	---	---	---	---	---
Subtotal of capital costs	---	---	---	---	---	817,380	---	---
Working capital**	---	---	---	---	---	179,166	---	---
AFDC‡	---	---	---	---	---	40,869	---	---
Grand total of capital costs	---	---	---	---	---	779,403	---	---

* Scale = 1,000 gpm; liquid density = 62 lbs/ft^3; vapor density = 50 lbs/ft^3.

† Mid-1978 dollars.

# Building.

** At one month of direct operating costs.

‡ Allowance for funds during construction at 5% of capital costs.

TABLE 20. SUMMARY OF FIRST YEAR O&M COSTS FOR DISTILLATION*

O&M Cost Category Module	Costs†							Quantities	
	Labor								
	Type 1 Operator 1 ($7.77/hr)	Type 2 Operator 2 ($9.19/hr)	Type 3 Laborer ($6.76/hr)	Energy Electrical ($0.035/KWH)	Maintenance Costs	Chemical Costs	Total	KWH (yr)	Natl. Gas ft3/yr
Steam generator	$ 1,179	$ 209	$ 15,586	$ 956,000	$ 2,798	$ 120,000	$ ---	---	2.48 x 10^9
Distillation column	17,703	10,406	20,513	---	1,602	---	---	---	---
Accumulator	---	---	---	---	398	---	---	---	---
Waste pump	---	---	---	1,730	---	---	---	49,429	---
Piping	---	---	179	---	276	---	---	---	---
Total	18,882	10,615	36,278	957,730	5,074	120,000	---	49,429	2.48 x 10^9
Supplemental O&M costs	---	---	---	---	1,348	---	---	---	---
Subtotal of direct O&M costs	---	---	---	---	---	---	1,149,927	---	---
Administrative overhead#	---	---	---	---	---	---	229,985	---	---
Debt service and amortization**	---	---	---	---	---	---	273,668	---	---
Real estate taxes and insurance‡	---	---	---	---	---	---	20,748	---	---
Total first year operating costs	---	---	---	---	---	---	1,674,328	---	---

* Scale = 1,000 gpm.
† Mid-1978 dollars.
# At 20% of direct operating costs.
** At 10% interest over 5 years.
‡ At 2% of total capital.

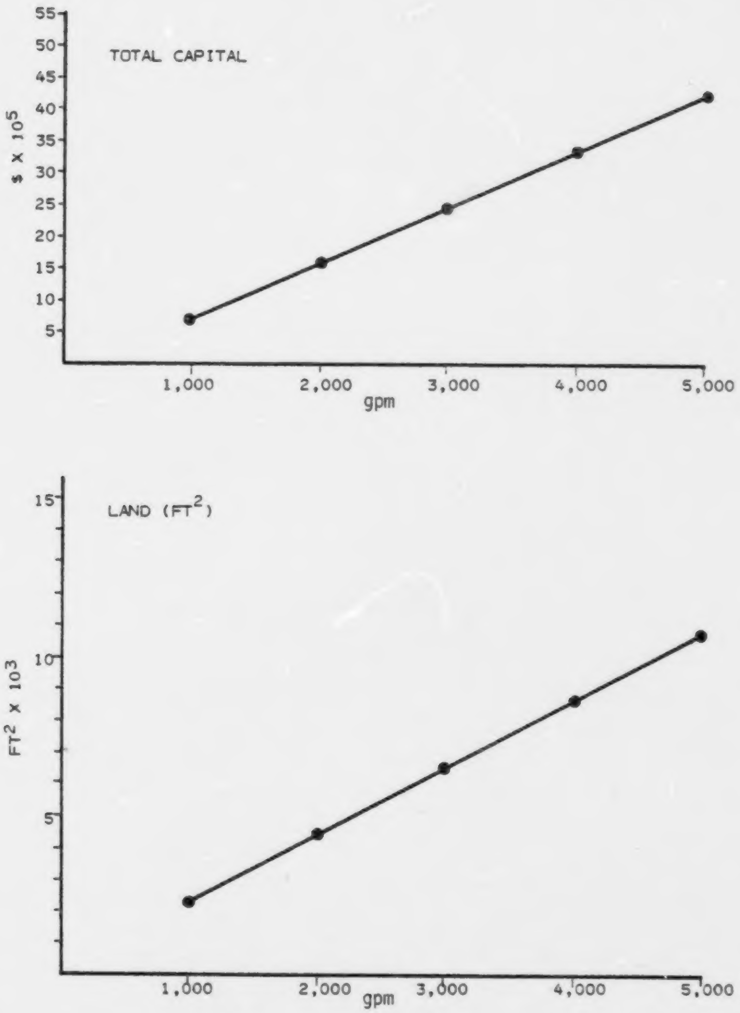


Figure 25. Distillation: changes in total capital costs with scale.

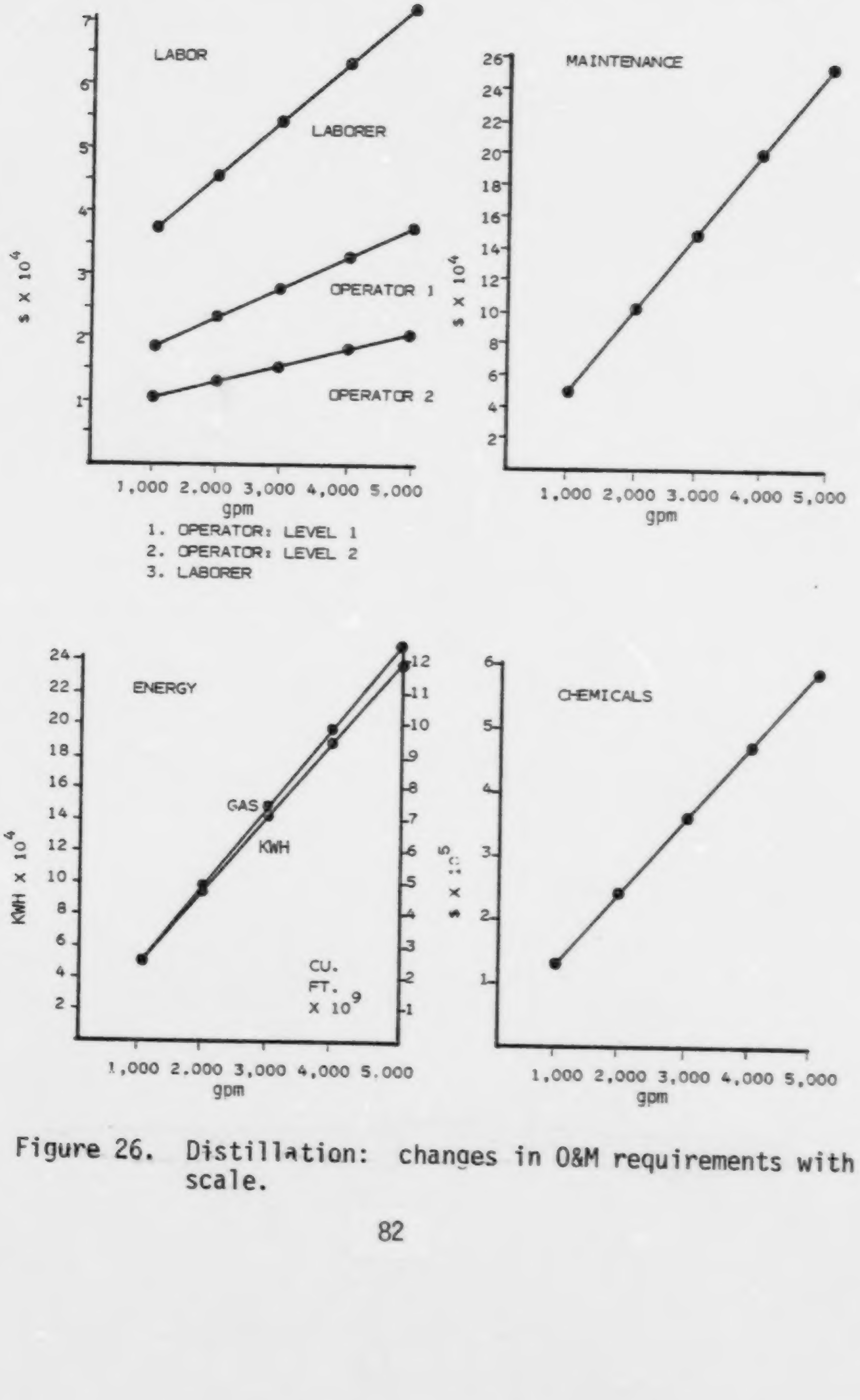


Figure 26. Distillation: changes in O&M requirements with scale.

TABLE 21. COMPUTATION OF LIFE CYCLE AVERAGE COST FOR IMPLEMENTING DISTILLATION (LIFETIME - 5 YEARS)

Item	Direct Operating Costs*	Indirect Operating Costs†	Sum Operating Costs	Present Value Annualized Costs#	Annual Quantity of Throughput (x 1,000 Gal.)**
YEAR 1‡	$1,149,927	$524,401	$1,674,328	$1,674,328	124,800
YEAR 2	1,264,920	547,399	1,812,319	1,647,579	124,800
YEAR 3	1,391,412	572,698	1,964,110	1,623,140	124,800
YEAR 4	1,530,553	600,526	2,131,079	1,601,080	124,800
YEAR 5	1,683,608	631,137	2,314,745	1,580,971	124,800
TOTALS			9,896,581	8,127,098	624,000
Simple Average (Per 1,000 Gal.)			$15.86		
Simple Average (Per Cubic Meter)			$ 4.19		
Life Cycle Average (Per 1,000 Gal.)				$13.02	
Life Cycle Average (Per Cubic Meter)				$ 3.44	

* Assumes 10% annual inflation.

† Inflation increases the administrative overhead only.

# Assumes a 10% interest/discount rate to the beginning of the first year of operation.

** 1,000 GPM x 60 min x 8 hrs/day x 260 days/yr.

‡ First year costs in mid-1978 dollars - for Chicago example.

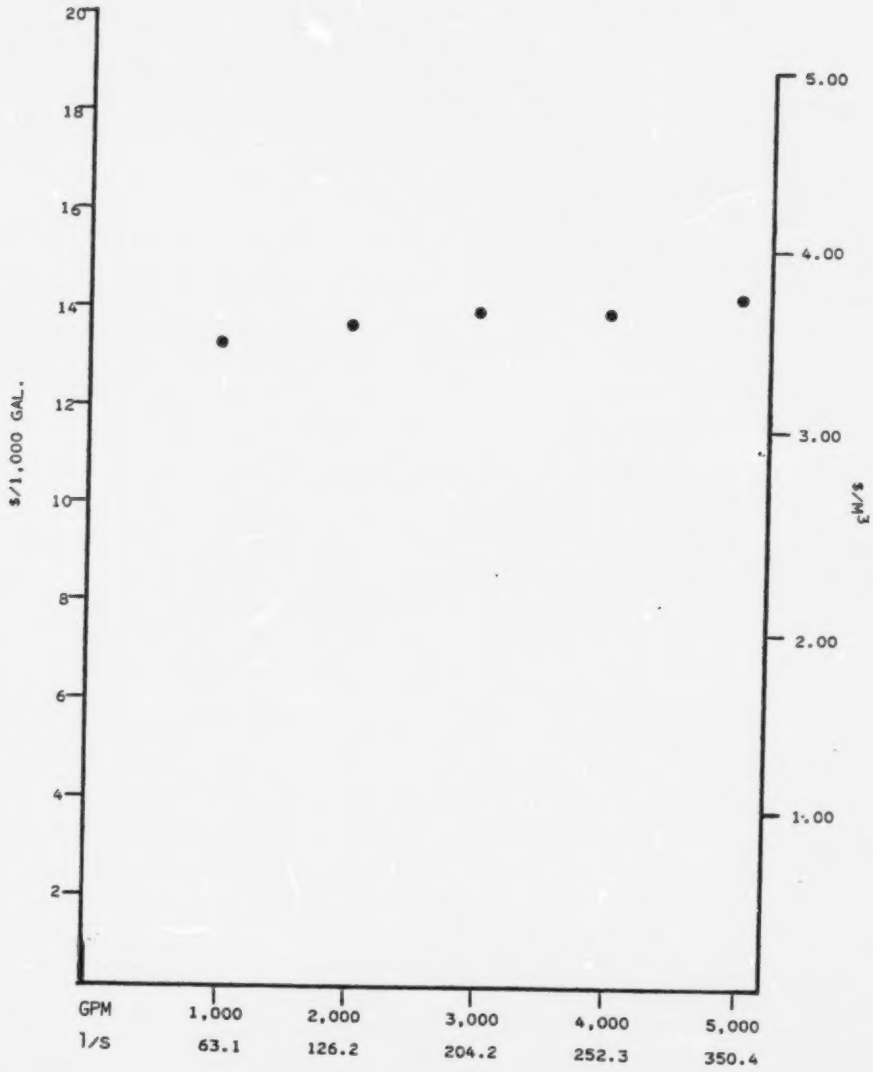


Figure 27. Distillation: life cycle costs at five scales of operation.

this analysis, dissolved air flotation therefore includes an aerated basin for biodegradation of organic hazardous wastes. The biological solids and effluents are passed into the flotation units which are comprised of rectangular tanks with separate chain-and-flight scum and sludge collectors (Figure 28). In order to achieve flotation of the suspended flocs, a stream of recycled effluent from the flotation unit is pressurized and blended with the inflow to be treated. Other methods include pressurizing all or part of the influent stream. As the pressurized stream is released into the flotation unit, tiny bubbles are formed which adhere to the solid matter; reducing the density of the aerated floc and allowing it to rise to the surface.

Design of units involves selection of values for a number of parameters, including the percent of recycle flow, operating pressure, pressurization retention time, air flow, and surface hydraulic loading, solids loading (area basis) and detention period.

Sludge concentrations depend more on detention time than solids loading. Solids capture in flotation is related to a parameter equal to the air-to-solids ratio divided by the product of surface hydraulic loading and dynamic viscosity.

Values of specific parameters used in actual applications vary widely. Typical ranges cited are as follows: (12).

Parameter	Range
Pressure, psig	25 to 70
Air-to-solids ratio, lb/lb	0.01 to 0.1
Sludge detention, min	20 to 60
Surface hydraulic loading, gpd/ft^2	500 to 4,000
Effluent recycled, percent	5 to 20

Changes in Configuration with Scale

There are no significant changes in configuration with scale for the range of operations studied (1,000 to 5,000 gpm). The aerated basin is assumed to be 10 ft. deep. Surface areas (SURFAR) in square feet are calculated as:

$$\text{SURFAR} = 0.042 \times \text{QINF} \times (\text{CINF} - \text{CEFL})/(1 \times 10 \times \text{KRATE})$$

where:

QINF = influent flow rate (gpm)
CINF = influent BOD (ppm)
CEFL = effluent BOD (ppm)
KRATE = reaction rate = 0.1 days $^{-1}$

The air flotation process is a simple package unit and is scaled up to provide sufficient volume and hence retention time for

85

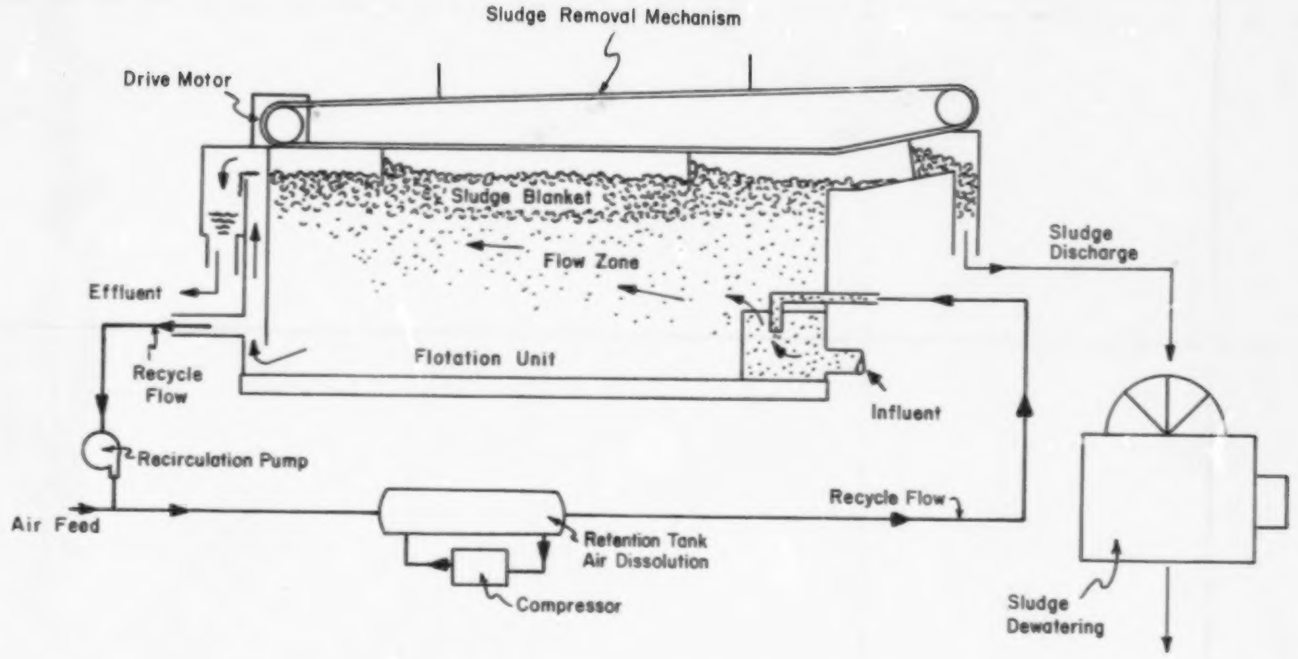

Sludge Removal Mechanism
Drive Motor
Sludge Blanket
Flow Zone
Effluent
Sludge Discharge
Recycle Flow
Flotation Unit
Influent
Recirculation Pump
Air Feed
Recycle Flow
Retention Tank Air Dissolution
Compressor
Sludge Dewatering

Figure 28. Schematic of dissolved air flotation including sludge dewatering.

flotation to occur. The chamber depth is 10 ft, and the surface area is calculated as QINF X TSS X 2.22 X 10^{-4}, where QINF is influent flow rate (gpm) and TSS is total suspended solids in parts per million. Additional dimensional calculations are included in the cost equations in Appendix F.

Applications

Dissolved air flotation (including the aerated basin) has been successfully applied to effluents in the organic chemicals industry (13). It is most commonly applied as a solids separation process after biodegradation of organic compounds. Other applications include concentration of inorganic flocs following chemical precipitation/flocculation reactions. The air flotation module replaces typical solids settling operations, such as sedimentation basins or clarifiers. (See "precipitation/flocculation/sedimentation").

Costs

Summaries of capital and first year operating costs for dissolved air flotation are shown in Tables 22 and 23. These estimates are based on mid-1978 costs for components, unit processes, labor, utilities, etc., as applicable in Chicago, Illinois. The estimates are based on the cost files in Appendices B and C, and the cost equations included in Appendix F.

As shown in Table 22, the most costly unit processes are the aerated basin and sludge dewatering system. The dissolved air flotation unit is relatively inexpensive; $5,480 for the structures (tank, foundation, etc.) and $1,434 for the mechanical equipment (compressor, sludge collectors, etc.) at the 1,000 gpm scale. The total capital cost for the 1,000 gpm example facility is $306,502.

Figure 29 shows the capital cost curve (exclusive of land costs) for five scales of operation and an accompanying curve showing the corresponding land area requirements. The capital costs per 1,000 gallons of waste treated fluctuates between $4.42 at 1,000 gpm to $1.83 at 2,000 gpm. The costs at 3,000 4,000 and 5,000 gpm are $2.01, $1.97 and $1.93, respectively. There is no overall pattern of major economy of scale.

The O&M requirements for dissolved air flotation as a function of scale are shown in Figure 30 . Labor and maintenance show significant scales of economy:

Scale (gpm)	1,000	2,000	3,000	4,000	5,000
Labor $/1,000 gal	0.57	0.36	0.29	0.25	0.23
Maintenance $/1,000 gal	0.12	0.10	0.08	0.07	0.07

TABLE 22. SUMMARY OF CAPITAL COSTS FOR DISSOLVED AIR FLOTATION*

Capital Cost Category Module	Costs†						Quantities
	Site Preparation	Structures	Mechanical Equipment	Electrical Equipment	Land	Total	Other Land (ft^2)
Air flotation	$ 22	$ 5,480	$ 1,434	---	$ 283	---	$ 381
Aerated basin	2,170	31,800	65,200	---	3,170	---	4,260
Sludge dewatering	66	1,120	166,000	$1,660	659	---	885
Waste pump	---	---	2,950	---	---	---	---
Sludge pump	---	---	613	---	---	---	---
Piping	225	---	1,130	---	---	---	---
Total	2,483	38,400	237,327	1,660	4,112	---	5,526
Supplemental capital costs	---	---	---	---	---	---	---
Subtotal of capital costs	---	---	---	---	---	$283,982	---
Working capital**	---	---	---	---	---	8,321	
AFDC‡	---	---	---	---	---	14,199	---
Grand total of capital costs	---	---	---	---	---	306,502	---

---

* Scale = 1,000 gpm; sludge wasting rate = .08 x 1,000 = 80 gpm.

† Mid-1978 dollars.

** At one month of direct operating costs.

‡ Allowance for funds during construction at 5% of capital costs.

TABLE 23. SUMMARY OF FIRST YEAR O&M COSTS FOR DISSOLVED AIR FLOTATION*

	Costs†							Quantities
	Labor							
O&M Cost Category Module	Type 1 Operator 1 ($7.77/hr)	Type 2 Operator 2 ($9.19/hr)	Type 3 Laborer ($6.76/hr)	Energy Electrical ($0.035/KWH)	Maintenance Costs	Chemical Costs	Total	Other KWHs/yr
Air flotation	$1,492	$ 326	$27,216	$ 1,740	$ 345	---	---	$ 49,728
Aerated basin	1,765	417	16,890	728	13,000	---	---	20,800
Sludge dewatering	1,963	603	20,509	9,170	1,710	---	---	262,080
Waste pump	---	---	---	1,730	---	---	---	---
Sludge pump	---	---	---	138	---	---	---	---
Piping	---	---	103	---	6	---	---	---
Total	5,220	1,346	64,718	13,506	15,061	---	---	332,608
Supplemental O&M costs	---	---	---	---	---	---	---	---
Subtotal of direct O&M costs	---	---	---	---	---	---	$ 99,851	---
Administrative overhead#	---	---	---	---	---	---	19,970	---
Debt service and amortization**	---	---	---	---	---	---	49,882	---
Real estate taxes and insurance‡	---	---	---	---	---	---	6,130	---
Total first year operating costs	---	---	---	---	---	---	175,883	---

* Scale = 1,000 gpm.

† Mid-1978 dollars.

# At 20% of direct operating costs.

** At 10% interest over 10 years.

‡ At 2% of total capital.

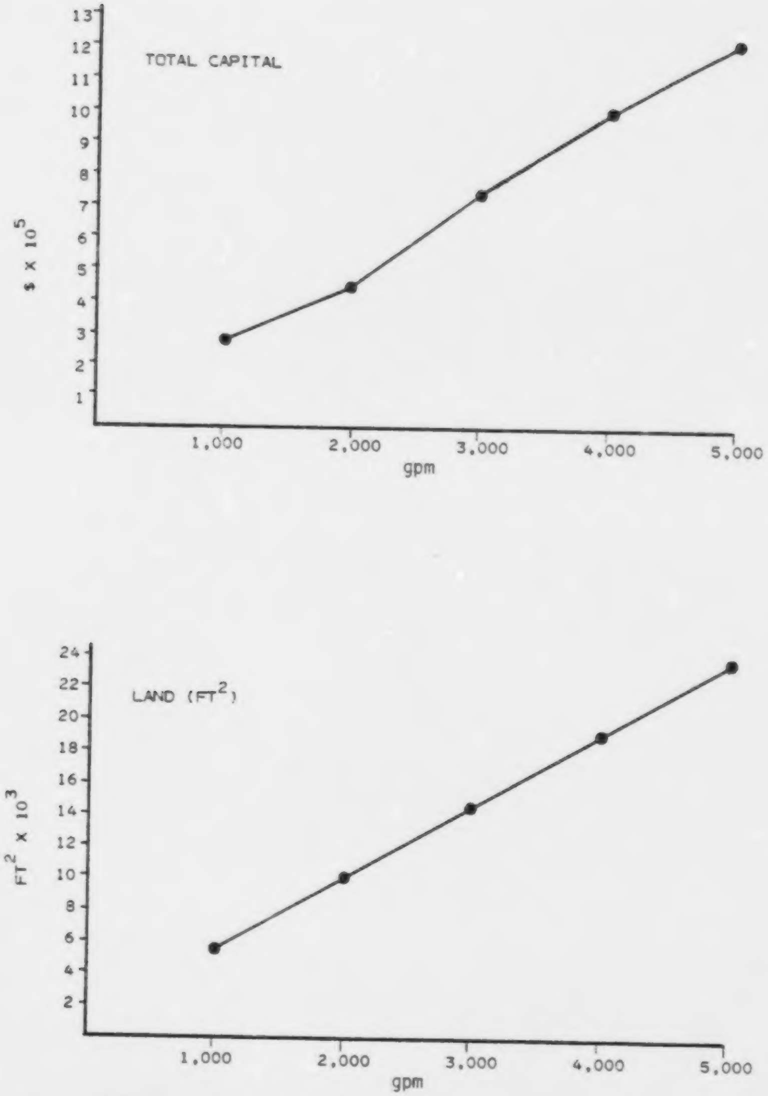


Figure 29. Dissolved air flotation: changes in total capital costs with scale.

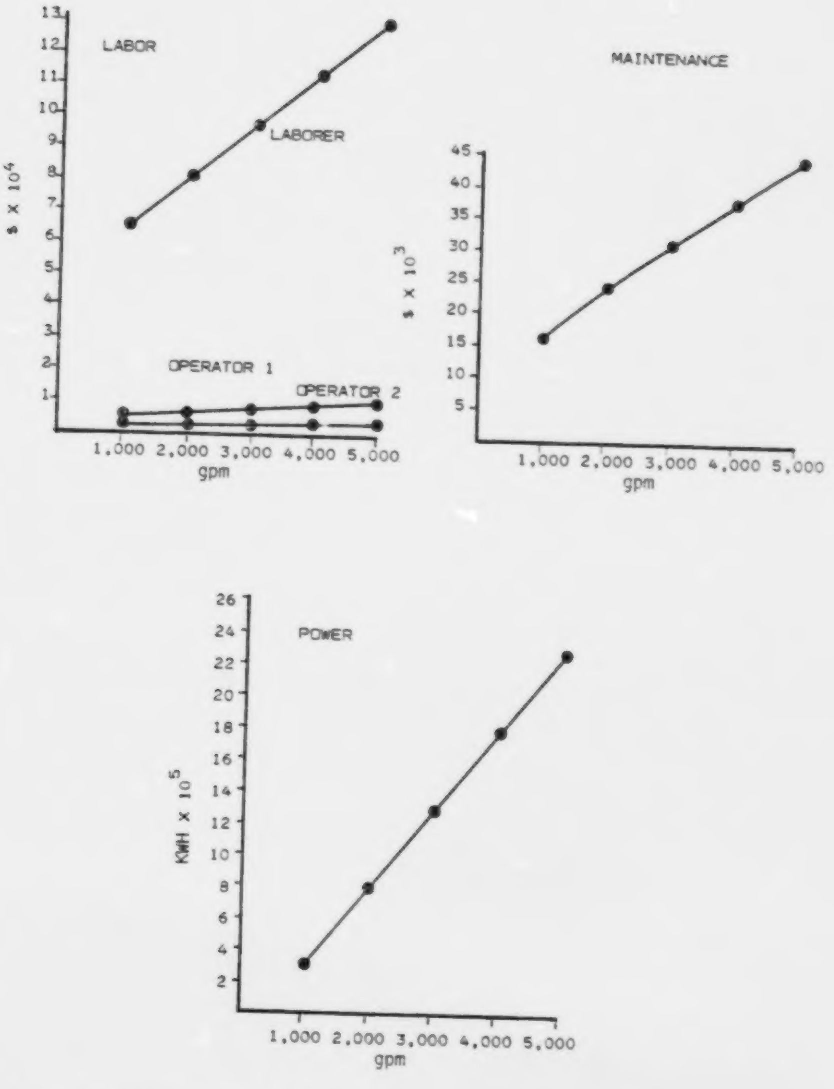


Figure 30. Dissolved air flotation: changes in O&M requirements with scale.

Energy also demonstrates a slight decrease from 2.67 to 2.62 KWH per 1,000 gallons treated, with increasing facility capacity. The largest energy demands stem from sludge dewatering.

The average cost of the example 1,000 gpm facility, over a 10-year life cycle, is \$1.26/1,000 gal (\$0.33/m^3) (Table 24). This competes favorably with other biological treatment technology costs. The change in the life cycle cost (per 1,000 gal treated) over the range of facility capacities studied is shown in Figure 31.

OIL/WATER SEPARATION

Description

The oil/water separator included in this assessment is similar to the General Electric (14) coalescing separator which can accommodate flows up to 350 gpm depending on the model and plate configuration selected (Figure 32). Larger flows are accommodated by site-constructed basins.

Oil/water mixtures are fed in at the head of the system. Gravimetric separation is accomplished and is a function of:

- Oil droplet size
- Retention time
- Density differences between the two phases
- Temperature.

Gravity feed is best, as pumping can cause emulsification. Demulsifying agents can be added to break emulsions and enhance separation. An accumulator tank is required to collect the separated oil.

Changes in Configuration with Scale

The model oil/water separator is a package unit and can accommodate input flow rates up to 150 gpm. For larger flows, a concrete basin is constructed on site and the coalescing plates are installed along with other plumbing and hardware. Under flow rates of 150 gpm, the entire package separator is costed as mechanical equipment. Larger scales of operation include the structural costs for the basin.

Applications

The use of oil/water separation is limited to liquid organic products that are immiscible and less dense in the water phase. The following are applications of oil/water separation to the example industry wastes:

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TABLE 24. COMPUTATION OF LIFE CYCLE AVERAGE COST FOR IMPLEMENTING DISSOLVED AIR FLOTATION (LIFETIME - 10 YEARS)

Item	Direct Operating Costs*	Indirect Operating Costs†	Sum Operating Costs	Present Value Annualized Costs#	Annual Quantity of Throughput (x 1,000 Gal.)**
YEAR 1‡	$ 99,851	$ 75,982	$175,833	$175,833	124,800
YEAR 2	109,836	77,979	187,815	170,741	124,800
YEAR 3	120,820	80,176	200,995	166,112	124,800
YEAR 4	132,902	82,592	215,494	161,904	124,800
YEAR 5	146,192	85,250	231,442	158,078	124,800
YEAR 6	160,811	88,174	248,985	154,600	124,800
YEAR 7	176,892	91,390	268,282	151,438	124,800
YEAR 8	194,581	94,928	289,509	148,564	124,800
YEAR 9	214,039	98,820	312,859	145,951	124,800
YEAR 10	235,443	103,101	338,544	143,576	124,800
TOTALS			2,469,758	1,576,797	1,248,000
Simple Average (Per 1,000 Gal.)			$1.98		
Simple Average (Per Cubic Meter)			$0.52		
Life Cycle Average (Per 1,000 Gal.)				$1.26	
Life Cycle Average (Per Cubic Meter)				$0.33	

---

* Assumes 10% annual inflation.

† Inflation increases the administrative overhead only.

# Assumes a 10% interest/discount rate to the beginning of the first year of operation.

** 1,000 GPM x 60 min x 8 hrs/day x 260 days/yr.

‡ First year costs in mid-1978 dollars - for Chicago example.

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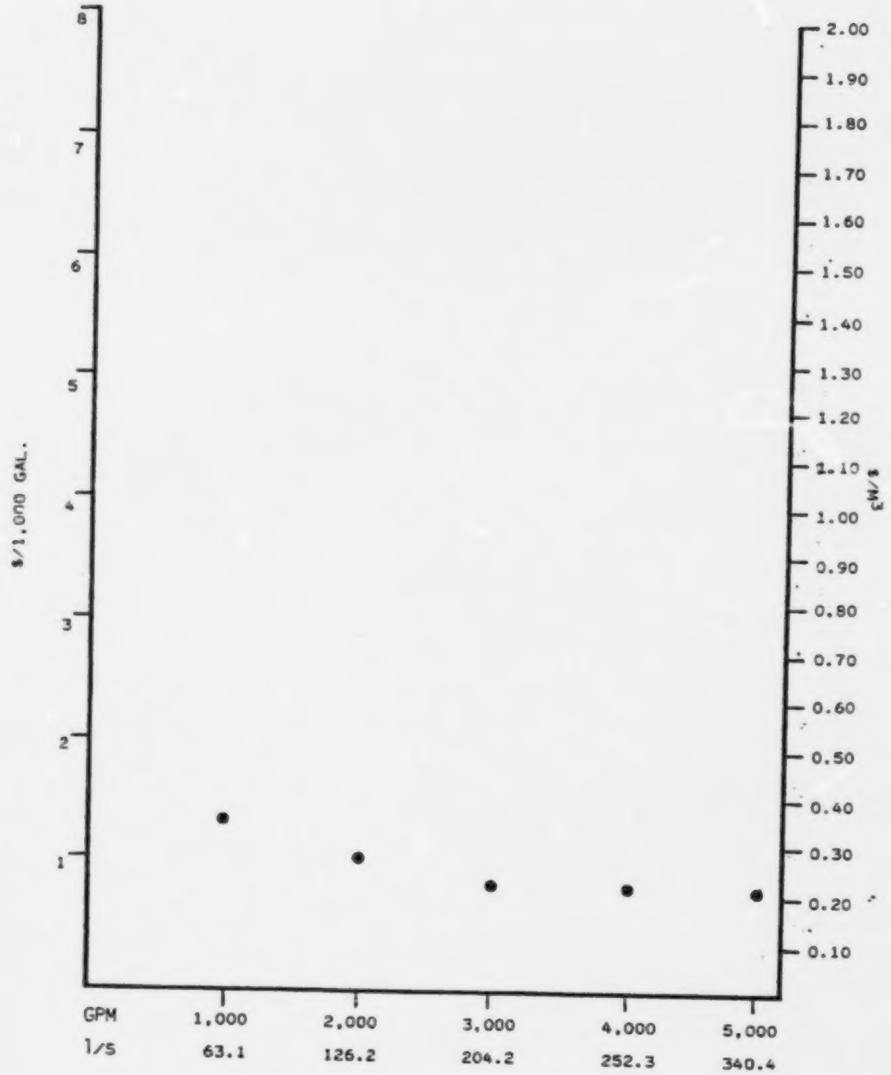

Figure 31. Dissolved air flotation: life cycle costs at five scales of operation.

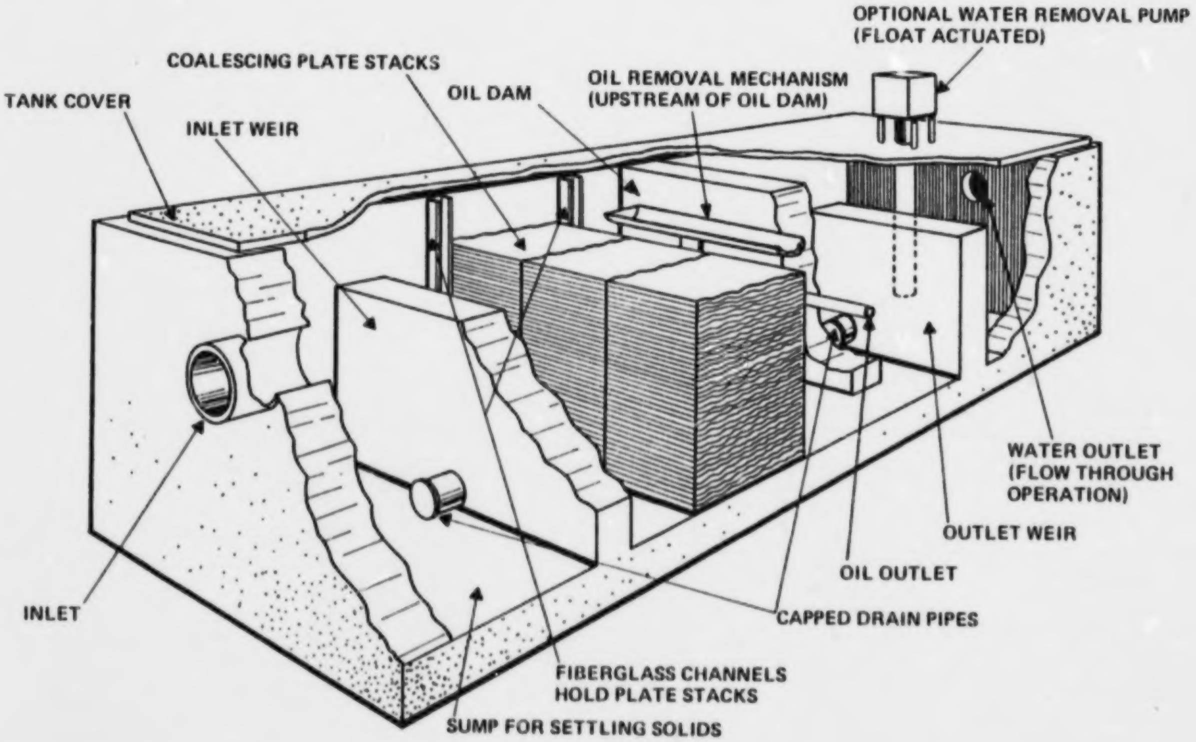
OPTIONAL WATER REMOVAL PUMP (FLOAT ACTUATED)
COALESCING PLATE STACKS
OIL DAM
OIL REMOVAL MECHANISM (UPSTREAM OF OIL DAM)
TANK COVER
INLET WEIR
WATER OUTLET (FLOW THROUGH OPERATION)
OUTLET WEIR
OIL OUTLET
INLET
CAPPED DRAIN PIPES
FIBERGLASS CHANNELS HOLD PLATE STACKS
SUMP FOR SETTLING SOLIDS

Figure 32. Coalescing oil/water separator design.

- Primary treatment of oil-bearing wastewaters from the organic industry

- Removal of degreasing solvents and other oils from metal plating and finishing baths.

Costs

Capital and first year operating costs are calculated for oil/water separation (Tables 25 and 26). The most costly element is the separation unit ($20,650 at 5,000 gpm). In using the cost model (Appendix F) for this technology, it was assumed that the oil/water mixture is emulsified, the oil has a specific gravity of 0.9, and the smallest oil droplet size is 10 µm after demulsification. The total capital costs for the Chicago-based example is $66,367. Major operating costs are labor and chemicals. The total first year operating costs are $193,809.

Figure 33 shows the capital costs (excluding land costs) at five scales of operation for the technology. The accompanying plot shows the land area requirements at the same scales of operation. The slope of the capital cost curve in Figure indicates that there is some economy of scale within the range studied. The capital expenditure (less land costs) per 1,000 gallons of waste treated is $0.13 at 1,000 gpm, decreases to $0.09 at 2,000 and 3,000 gpm, and is $0.08 at 4,000 and 5,000 gpm. The larger difference between the 1,000 gpm and larger scales of operation is due to the shift from package to site-installed facilities.

Figure 34 shows the fluctuation in O&M requirements with scale for the model facility (operating 8 hr/day and 260 day/yr). Total labor costs are low ($10,737 at 1,000 gpm) compared to other technologies and reflect the minimal supervision and servicing necessary to operate oil/water separation. Maintenance costs demonstrate marked economies of scale; and this is due to the simplicity of mechanical equipment and servicing at all scales of operation. Power requirements are constant for all scales studied (0.40 kwh/1,000 gal). Chemical demand increases with scale. This is attributable to the need for additional demulsifying chemicals for larger installations where high volume pumping and short circuiting of the basin flow can be a problem.

The average cost of the Chicago-based model facility over a life cycle of 10 years is calculated in Table 27 . The life cycle average cost is $0.30/1,000 gallons ($0.08/m^3) for the 5,000 gpm facility. Figure 35 shows the variation in the average cost with scale. The reduction in capital costs from 1,000 to 2,000 gpm is evidenced in the life cycle calculations. Oil/water separation demonstrates low capital and operational costs and should be applied wherever oil bearing wastes can be

TABLE 25. SUMMARY OF CAPITAL COSTS FOR OIL/WATER SEPARATION*

Capital Cost Category Module	Costs†						Quantities
	Site Preparation	Structures	Mechanical Equipment	Electrical Equipment	Land	Total	Other Land (ft^2)
Oil/water separator	$ 28	$1,083	$20,650	---	$ 275	---	$ 370
Accumulator	586	4,270	4,520	---	473	---	636
Waste pump	---	---	10,800	---	---	---	---
Chem. feed	389	2,130	2,840	---	321	---	432
Chem. pump	---	---	1,470	---	---	---	---
Piping	225	---	1,130	---	---	---	---
Total	1,228	7,483	41,410	---	1,069	---	1,438
Supplemental capital costs	---	---	---	---	---	---	---
Subtotal of capital costs	---	---	---	---	---	$51,190	---
Working capital**	---	---	---	---	---	12,617	---
AFDC‡	---	---	---	---	---	2,560	---
Grand total of capital costs	---	---	---	---	---	66,367	---

* Scale = 5,000 gpm; oil/water mixture-emulsified oil specific gravity = 0.9, smallest oil droplet size 10 μm after demulsification.

† Mid-1978 dollars.

** At one month of direct operating costs.

‡ Allowance for funds during construction at 5% of capital costs.

TABLE 26. SUMMARY OF FIRST YEAR O&M COSTS FOR OIL/WATER SEPARATION*

O&M Cost Category Module	Costs†							Quantities
	Labor							
	Type 1 Operator 1 ($7.77/hr)	Type 2 Operator 2 ($9.19/hr)	Type 3 Laborer ($6.76/hr)	Energy Electrical ($0.035/KWH)	Maintenance Costs	Chemical Costs	Total	Other KWHs/yr
Oil/water separator	$892	$195	$20,000	---	$ 581	---	---	---
Accumulator	---	---	---	---	300	---	---	---
Waste pump	---	---	---	$8,630	---	---	---	$246,571
Chem. feed	12	14	184	---	398	$120,000	---	---
Chem. pump	---	---	---	86	---	---	---	2,466
Piping	---	---	103	---	6	---	---	---
Total	904	209	20,287	8,716	1,285	120,000	---	249,037
Supplemental O&M costs	---	---	---	---	---	---	---	---
Subtotal of direct O&M costs	---	---	---	---	---	---	$151,401	---
Administrative overhead#	---	---	---	---	---	---	30,280	---
Debt service and amortization**	---	---	---	---	---	---	10,801	---
Real estate taxes and insurance‡	---	---	---	---	---	---	1,327	---
Total first year operating costs	---	---	---	---	---	---	193,809	---

---

* Scale = 5,000 gpm.
† Mid-1978 dollars.
# At 20% of direct operating costs.
** At 10% interest over 10 years.
‡ At 2% of total capital.

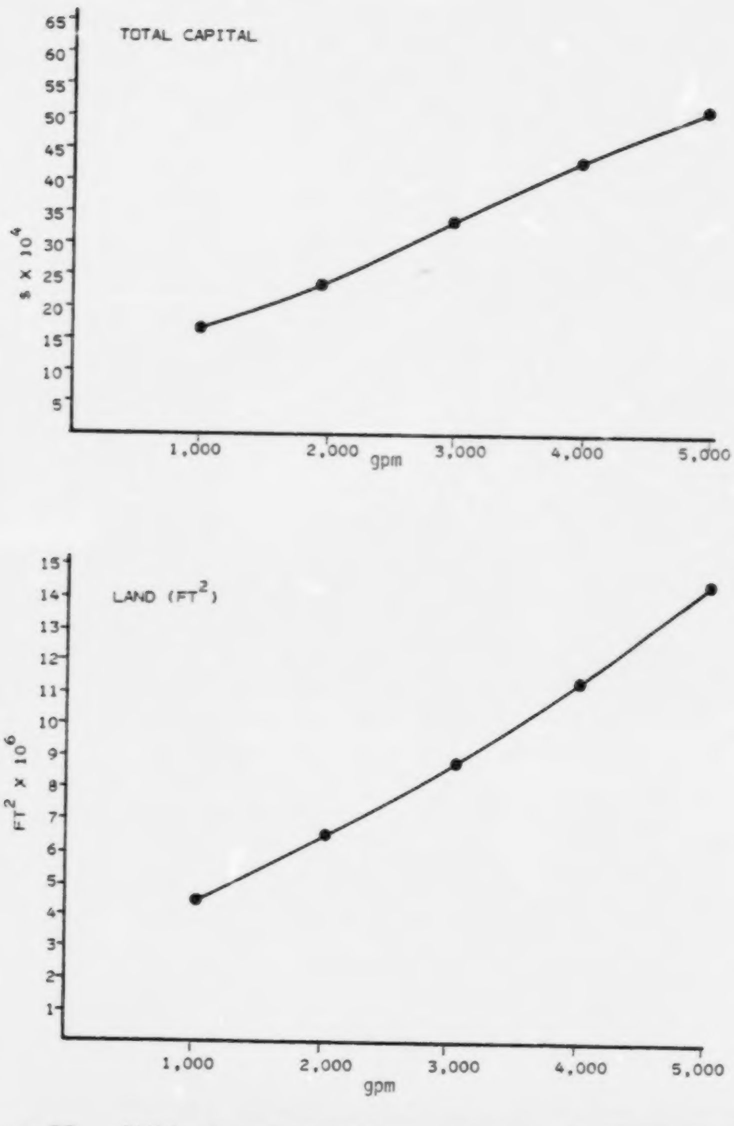

Figure 33. Oil/water separation: changes in total capital costs with scale.

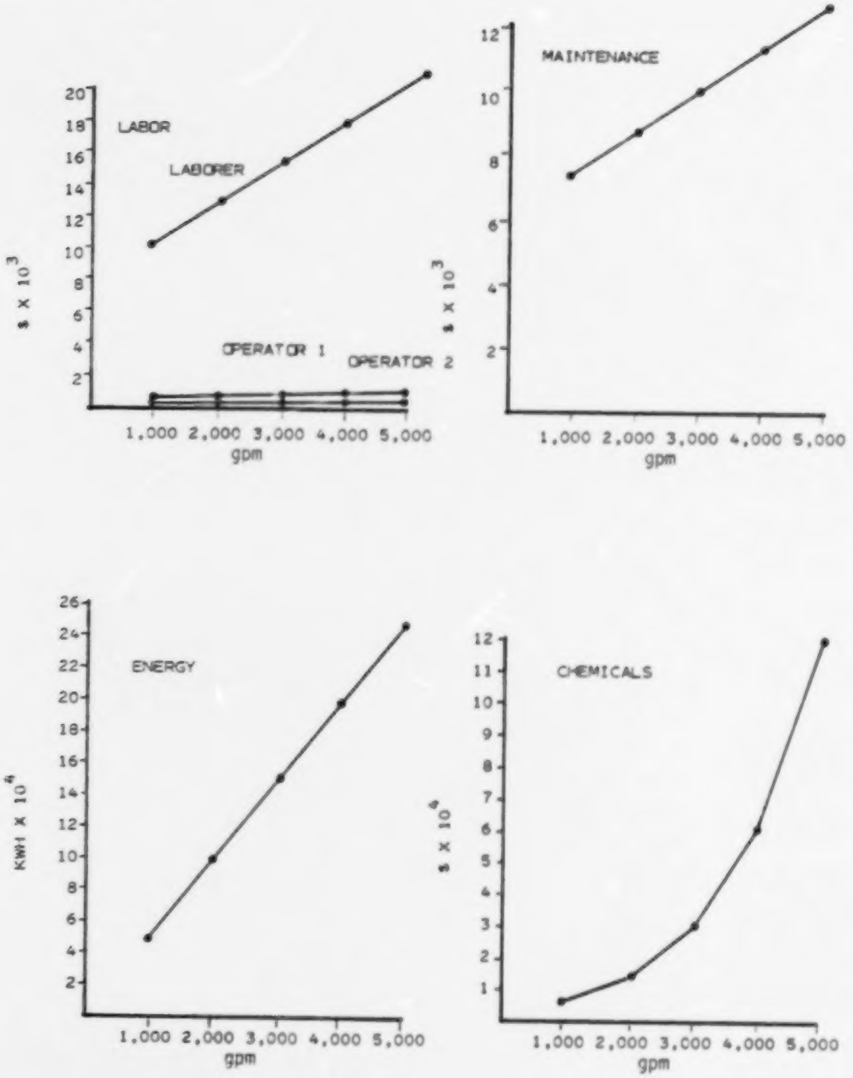

Figure 34. Oil/water separation: changes in O&M requirements with scale.

TABLE 27. COMPUTATION OF LIFE CYCLE AVERAGE COST FOR IMPLEMENTING OIL/WATER SEPARATION (LIFETIME - 10 YEARS)

Item	Direct Operating Costs*	Indirect Operating Costs†	Sum Operating Costs	Present Value Annualized Costs#	Annual Quantity of Throughput (x 1,000 Gal.)**
YEAR 1‡	$151,401	$42,408	$193,809	$193,809	624,000
YEAR 2	166,541	45,436	211,977	192,707	624,000
YEAR 3	183,196	48,767	231,962	191,704	624,000
YEAR 4	201,515	52,431	253,946	190,793	624,000
YEAR 5	221,666	56,461	278,128	189,965	624,000
YEAR 6	243,833	60,895	304,728	189,212	624,000
YEAR 7	268,216	65,771	333,987	188,527	624,000
YEAR 8	295,038	71,136	366,173	187,905	624,000
YEAR 9	324,541	77,036	401,578	187,339	624,000
YEAR 10	356,996	83,527	440,523	186,825	624,000
TOTALS			3,016,811	1,898,786	6,240,000
Simple Average (Per 1,000 Gal.)			$0.48		
Simple Average (Per Cubic Meter)			$0.13		
Life Cycle Average (Per 1,000 Gal.)				$0.30	
Life Cycle Average (Per Cubic Meter)				$0.08	

* Assumes 10% annual inflation.

† Inflation increases the administrative overhead only.

# Assumes a 10% interest/discount rate to the beginning of the first year of operation.

** 5,000 GPM x 60 min x 8 hrs/day x 260 days/yr.

‡ First year costs in mid-1978 dollars - for Chicago example.

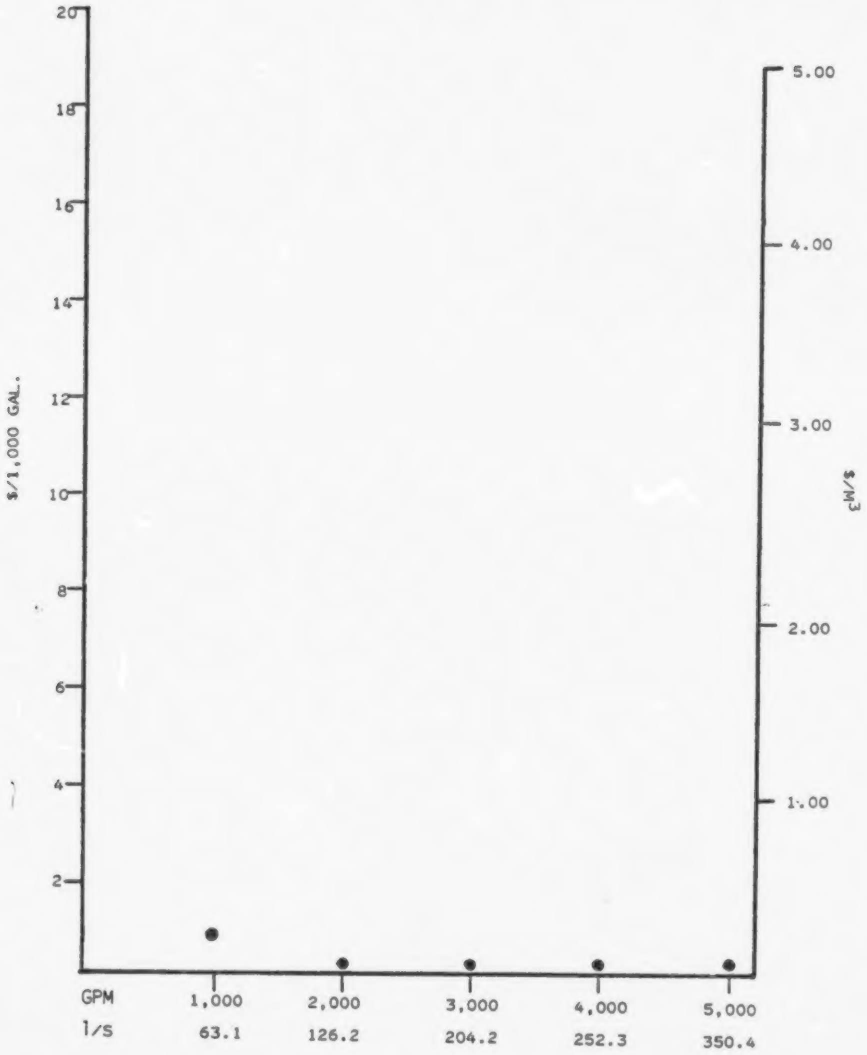

Figure 35. Oil/water separation: life cycle costs at five scales of operation.

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demulsified and treated through gravimetric means.

REVERSE OSMOSIS

Description

The heart of an industrial waste reverse osmosis plant is the reverse osmosis modules (Figure 36). These devices are assembled into racks to accommodate the desired flow rate in a given treatment plant. Since 1970 the tubular module has been improved to yield the spiral-wound cell (Gulf-General) and the hollow tube cell (DuPont and Dow); all working on the same general principal. Theoretically, reverse osmosis is induced by applying a high pressure to a suitable thin membrane, which at the same time rejects the salt molecules and thereby separates a relatively salt-free water stream. The remaining salt solution is concentrated and flows out of the system.

Rinse waters from a specific process can be treated using reverse osmosis; the water product is returned for rinsing, and the concentrates, possibly after further concentration by evaporation are extracted for disposal.

Suitable membrane materials for cyanide- and chromium-type rinse-water reconcentration are not yet commercially available.

Care must be exercised with reverse osmosis systems so that the waste does not contain certain collodial substances or heterogeneous matter; otherwise, these may in time reduce the permeability of the membrane.

Changes in Configuration with Scale

Additional banks of reverse osmosis modules are utilized to treat increased flow rates. For small-scale organic waste concentration, 5 modules are required for every gpm of capacity.

Applications

The following applications are documented for reverse osmosis:

- Separation of plating salts
- Reclamation of rinse waters for reuse
- Reclamation of metals from plating
- Removal of residual total dissolved solids
- Removal of certain trace organic compounds (e.g., pesticides)

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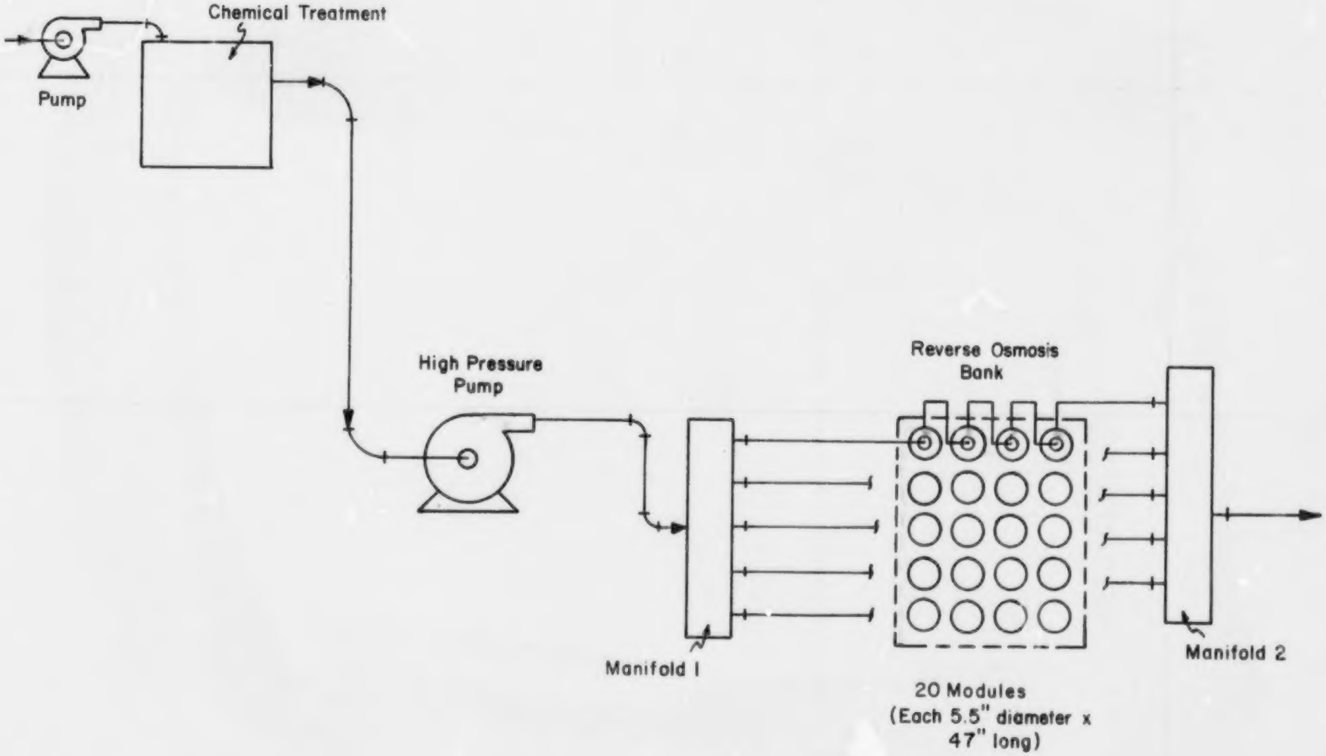
Pump
Chemical Treatment
High Pressure Pump
Reverse Osmosis Bank
Manifold I
Manifold 2
20 Modules (Each 5.5" diameter x 47" long)

Figure 36. Typical treatment plant employing reverse osmosis.

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Costs

Capital costs for reverse osmosis are itemized in Table 28. Over 85 percent of the total mechanical equipment costs are attributable to the reverse osmosis modules and manifold system. The total capital cost for a 1,000 gpm Chicago-based facility is $633,699 (mid-1978 dollars).

Table 29 summarizes the first year operating costs. Almost 75 percent of the direct O&M costs are attributable to the requirements for antifouling chemical feeds. The total first year operating costs, including administrative overhead ($121,363), debt service and amortization ($130,165) and real estate taxes and insurance ($12,674) are $871,016.

Figure 37 shows the capital costs (excluding land costs) for five scales of operation and the corresponding land requirements for reverse osmosis. The capital cost for the 1,000 gpm facility is equal to $4.41/1,000 gallons of waste treated. This unit cost decreases to $4.27 at 2,000 gpm and then increases to $4.86 at 5,000 gpm. The increased cost at the larger scales of operation is attributed to the need for larger and more complex module arrangements and support facilities.

The O&M requirements for reverse osmosis as a function of scale are shown in Figure 38 . Total labor costs are $86,906/yr at 1,000 gpm and $173,335/yr at 5,000 gpm. A significant portion of these costs are attributable to the requirement for skilled operators to constantly oversee the treatment operations. Maintenance and energy demands are fairly constant over the range studied and chemical costs increase with increased capacity.

The average cost of the example facility over a life cycle of 7 years, is calculated in Table 30 . The life cycle average cost for the 1,000 gpm facility is $6.71/1,000 gal ($1.77/m^3). Figure 39 shows the average cost (per 1,000 gal) at five scales of operation. No economy of scale is observed and, in fact, the average cost increases from $6.71 to $7.25/1,000 gal over the range studied. This is attributed to the corresponding increase in capital and chemical costs per unit volume of waste treated.

ULTRAFILTRATION

Description

Ultrafiltration installations closely resemble those described for reverse osmosis (Figure 40). The range of pore size in the ultrafiltration module (0.002 to 0.004 micron) limits the applications to that of removal of finely emulsified oils, or other chemicals and suspended solids, from the feed stream. This is distinct from reverse osmosis, which is also capable of concentrating dissolved salts, through use of

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TABLE 28. SUMMARY OF CAPITAL COSTS FOR REVERSE OSMOSIS*

Capital Cost Category Module	Costs†						Quantities
	Site Preparation	Structures	Mechanical Equipment	Electrical Equipment	Land	Total	Other Land (ft^2)
Reverse osmosis	$ 326	$ 6,350	$355,000	$17,800	$3,230	---	$4,340
Liquid feed	1,127	10,700	8,320	---	882	---	1,186
Accumulator	586	4,270	4,520	---	473	---	636
Chem. pump	---	---	1,530	---	---	---	---
Waste pump	---	---	2,950	---	---	---	---
Piping	675	---	39,300	---	---	---	---
Total	2,714	21,320	411,620	17,800	4,585	---	6,162
Supplemental capital costs	---	97,324#	---	---	---	---	---
Subtotal of capital costs	---	---	---	---	---	$555,363	---
Working capital**	---	---	---	---	---	50,568	---
AFDC‡	---	---	---	---	---	27,768	---
Grand total of capital costs	---	---	---	---	---	633,699	---

* Scale = 1,000 gpm.

† Mid-1978 dollars.

# Building.

** At one month of direct operating costs.

‡ Allowance for funds during construction at 5% of capital costs.

TABLE 29. SUMMARY OF FIRST YEAR O&M COSTS FOR REVERSE OSMOSIS*

	Costs†							Quantities	
	Labor								
O&M Cost Category Module	Type 1 Operator 1 ($7.77/hr)	Type 2 Operator 2 ($9.19/hr)	Type 3 Laborer ($6.76/hr)	Energy Electrical ($0.035/KWH)	Maintenance Costs	Chemical Costs	Total	KWH (yr)	Other COACL gal/yr
Reverse osmosis	$35,357	$10,425	$40,970	$15,700	$50,300	$367,000	---	$877,200	---
Liquid feed	---	---	---	---	398	82,600	---	---	$24,960
Accumulator	---	---	---	---	600	---	---	---	---
Chem. pump	---	---	---	35	---	---	---	1,000	---
Waste pump	---	---	---	1,730	---	---	---	49,429	---
Piping	---	---	154	---	197	---	---	---	---
Total	35,357	10,425	41,124	17,465	51,495	449,600	---	927,629	24,960
Supplemental O&M costs	---	---	---	---	1,348	---	---	---	---
Subtotal of direct O&M costs	---	---	---	---	---	---	$606,814	---	---
Administrative overhead#	---	---	---	---	---	---	121,363	---	---
Debt service and amortization**	---	---	---	---	---	---	130,165	---	---
Real estate taxes and insurance‡	---	---	---	---	---	---	12,674	---	---
Total first year operating costs	---	---	---	---	---	---	871,016	---	---

* Scale = 1,000 gpm.
† Mid-1978 dollars.
# At 20% of direct operating costs.
** At 10% interest over 7 years.
‡ At 2% of total capital.

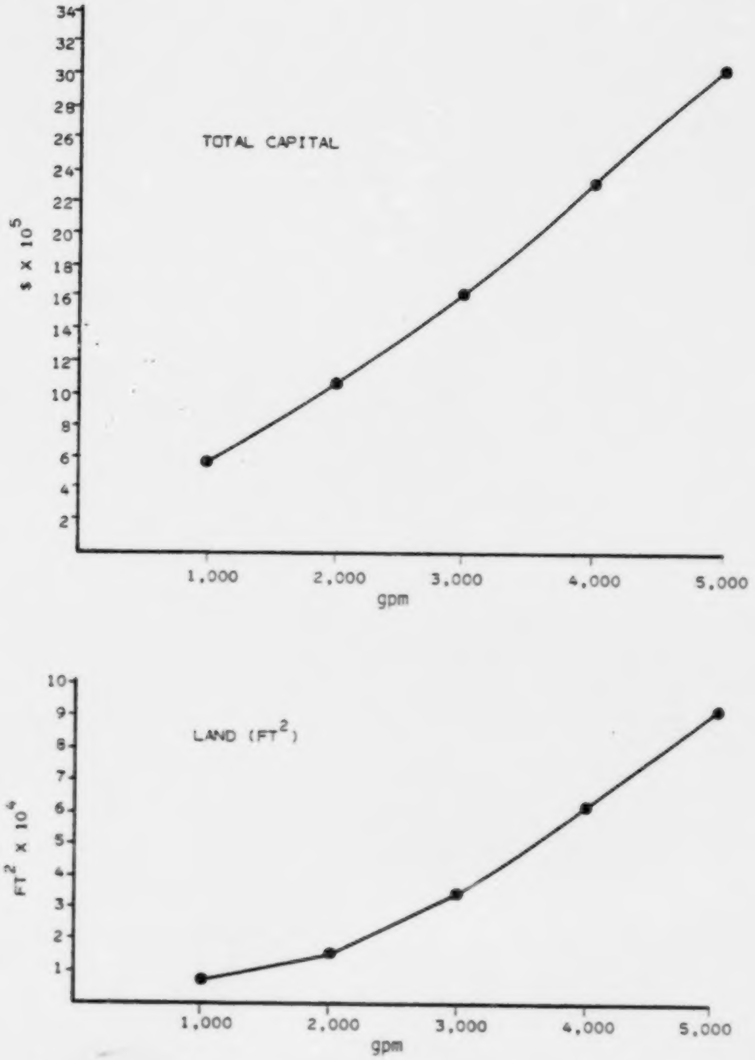

Figure 37. Reverse osmosis: changes in total capital costs with scale.

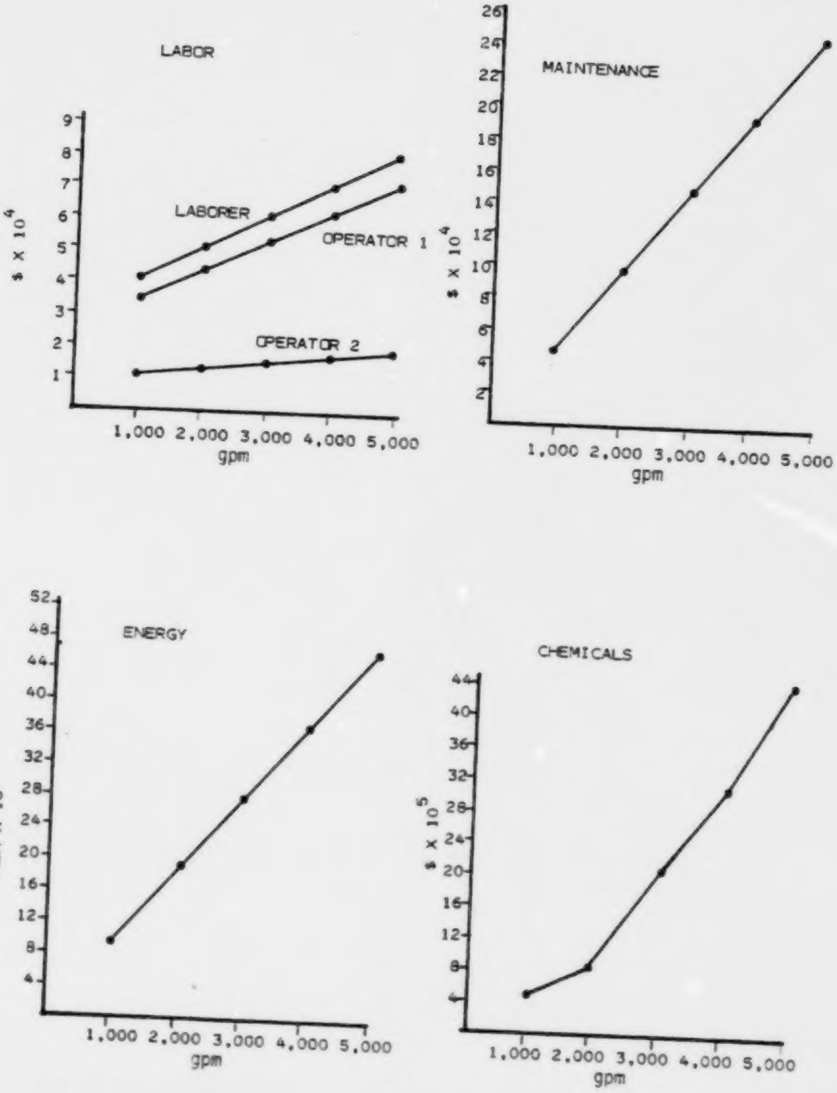

Figure 38. Reverse osmosis: changes in O&M requirements with scale.

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TABLE 30. COMPUTATION OF LIFE CYCLE AVERAGE COST FOR IMPLEMENTING REVERSE OSMOSIS (LIFETIME - 7 YEARS)

Item	Direct Operating Costs*	Indirect Operating Costs†	Sum Operating Costs	Present Value Annualized Costs#	Annual Quantity of Throughput (x 1,000 Gal.)**
YEAR 1‡	$ 606,814	$264,202	$ 871,016	$871,016	124,800
YEAR 2	667,495	276,338	943,834	858,031	124,800
YEAR 3	734,245	289,688	1,023,933	846,226	124,800
YEAR 4	807,669	304,373	1,112,043	835,494	124,800
YEAR 5	888,436	320,527	1,208,963	825,738	124,800
YEAR 6	977,280	338,295	1,315,575	816,869	124,800
YEAR 7	1,075,008	357,841	1,432,849	808,806	124,800
TOTALS			7,908,212	5,862,180	873,600
Simple Average (Per 1,000 Gal.)			$9.05		
Simple Average (Per Cubic Meter)			$2.39		
Life Cycle Average (Per 1,000 Gal.)				$6.71	
Life Cycle Average (Per Cubic Meter)				$1.77	

---

* Assumes 10% annual inflation.

† Inflation increases the administrative overhead only.

# Assumes a 10% interest/discount rate to the beginning of the first year of operation.

** 1,000 GPM x 60 min x 8 hrs/day x 260 days/yr.

‡ First year costs in mid-1978 dollars - for Chicago example.

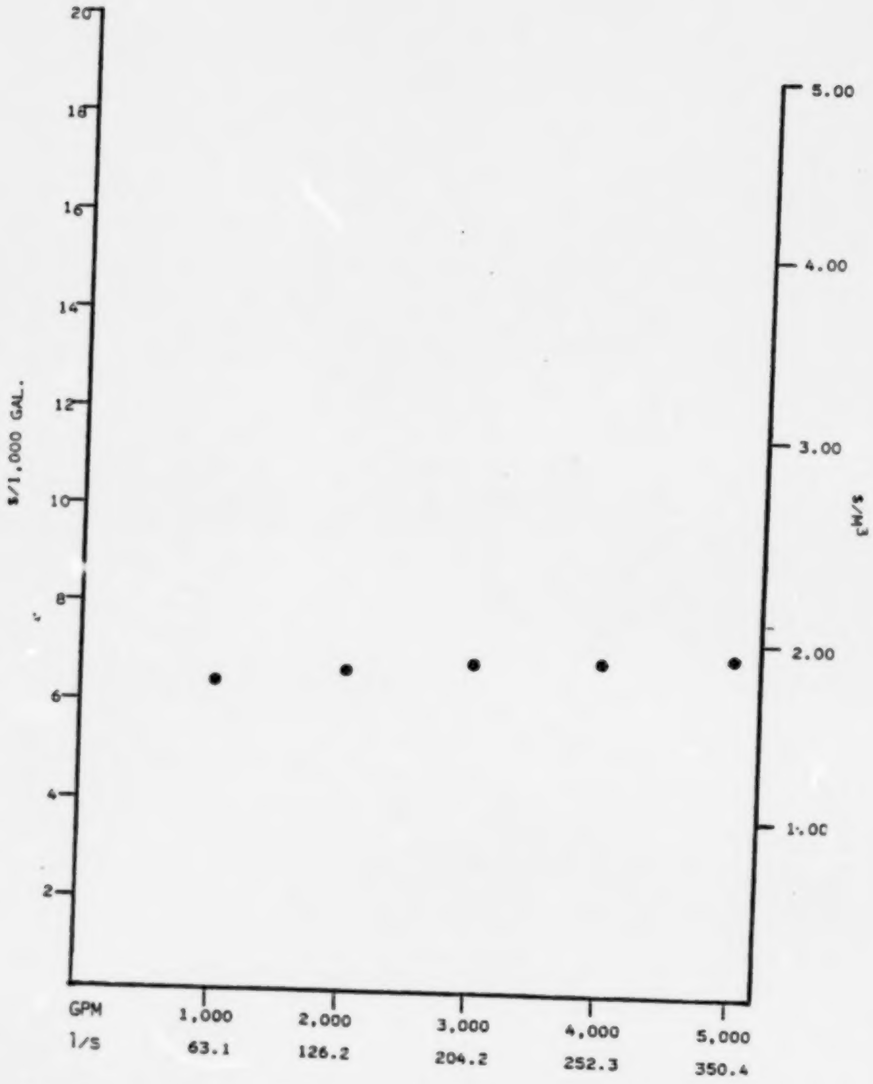

Figure 39. Reverse osmosis: life cycle costs at five scales of operation.

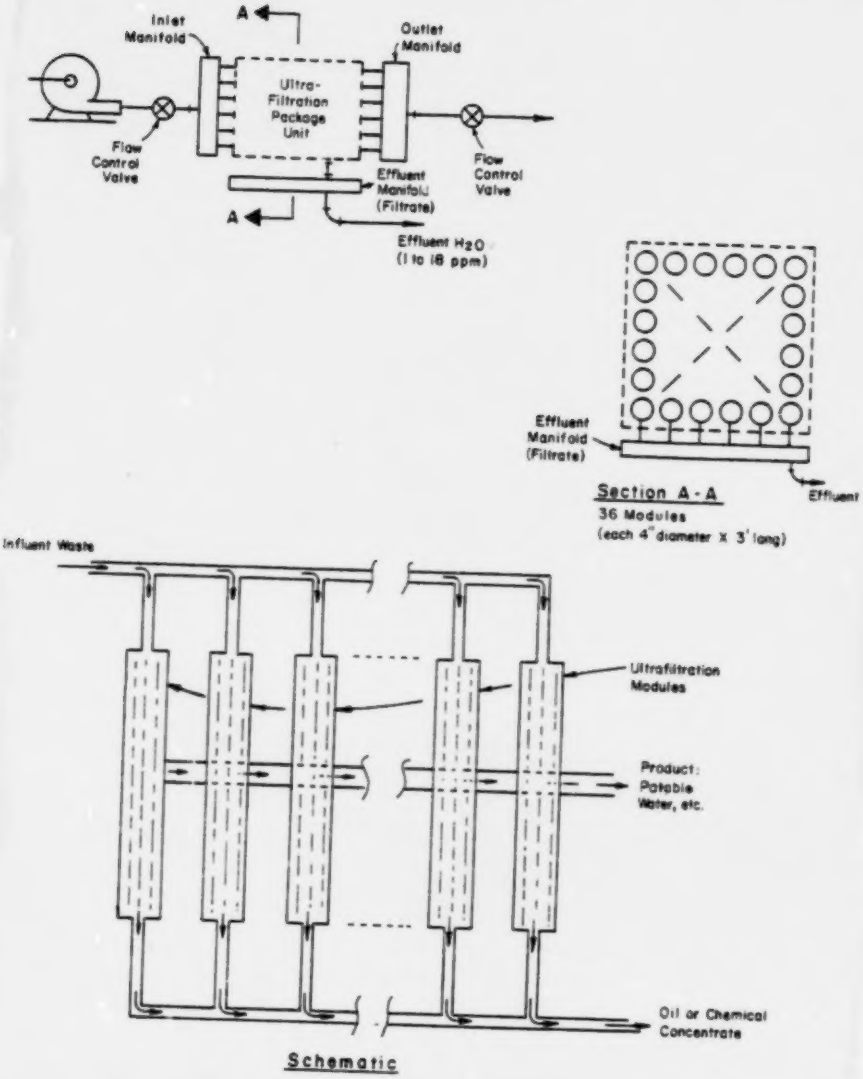
Inlet Manifold
A
Outlet Manifold
Ultra-Filtration Package Unit
Flow Control Valve
Effluent Manifold (Filtrate)
Flow Control Valve
A
Effluent H2O (1 to 18 ppm)
Effluent Manifold (Filtrate)
Effluent
Section A-A
36 Modules (each 4" diameter X 3' long)
Influent Waste
Ultrafiltration Modules
Product: Potable Water, etc.
Oil or Chemical Concentrate
Schematic

Figure 40. Typical ultrafiltration plant.

extremely 'fine' membrane elements (hyper filtration).

Streams in the flux range of 5 to 50 gpd/ft^2 of membrane enter the module flowing past the membrane elements oriented parallel to the flow vector. Fouling by microorganisms or organic deposits is minimized by the scouring action of the feed stream. Operating pressure is in the range 10 to 100 psig, compared with the 500 to 1,500 psig that characterizes reverse osmosis modules. Backflushing is conducted regularly to maintain adequate flow rate.

Changes in Configuration with Scale

Increases in flow demand require little more than the addition of a greater number of ultrafiltration modules oriented in parallel. This requires enlargement of header piping and increased pumping capacity. Each square foot of membrane area can accommodate up to .035 gpm.

Applications

Present commercial applications include processing of the following acquatic industrial waste streams:

- Electrocoat paint rejuvenation and rinse water recovery
- Protein recovery from cheese whey
- Metal machinery-oil emulsion treatment
- Textile sizing (polyvinyl alcohol) wastes.

Ultrafiltration is best applied to on-site, single waste streams. Applications to large volumes of varying waste types are still in the developmental stages.

Costs

The capital and O&M unit cost files (Appendices B and C) are used together with the cost equations in Appendix F to derive capital and first year operating costs for ultrafiltration (Tables 31and 32). All costs are adjusted for inflation to mid-1978 values and are based on charges as they exist for the City of Chicago, Illinois.

The breakdown of costs for ultrafiltration is similar to that for reverse osmosis; the most costly elements are the ultrafiltration modules and associated equipment. The major O&M costs are associated with the chemicals necessary for module defouling. The total capital and first year operating costs are $768,187 and $417,038, respectively for the 1,000 gpm facility

TABLE 31. SUMMARY OF CAPITAL COSTS FOR ULTRAFILTRATION*

Capital Cost Category Module	Costs†						Quantities
	Site Preparation	Structures	Mechanical Equipment	Electrical Equipment	Land	Total	Other Land (ft^2)
Ultrafiltration	$1,680	$62,300	$456,000	$22,800	$ 41	---	$ 55
Liquid feed	1,127	10,700	8,320	---	882	---	1,186
Accumulator	586	4,2[illegible]0	4,520	---	473	---	636
Chem. pump	---	---	1,530	---	---	---	---
Waste pump	---	---	2,950	---	---	---	---
Piping	675	---	39,300	---	---	---	---
Total	4,068	77,270	512,620	22,800	1,396	---	1,877
Supplemental capital costs	---	97,324#	---	---	---	---	---
Subtotal of capital costs	---	---	---	---	---	$715,478	---
Working capital**	---	---	---	---	---	16,935	---
AFDC‡	---	---	---	---	---	35,774	---
Grand total of capital costs	---	---	---	---	---	768,187	---

* Scale = 1,000 gpm.

† Mid-1978 dollars.

# Building.

** At one month of direct operating costs.

‡ Allowance for funds during construction at 5% of capital costs.

TABLE 32. SUMMARY OF FIRST YEAR O&M COSTS FOR ULTRAFILTRATION*

O&M Cost Category Module	Costs†							Quantities
	Labor							
	Type 1 Operator 1 ($7.77/hr)	Type 2 Operator 2 ($9.19/hr)	Type 3 Laborer ($6.76/hr)	Energy Electrical ($0.035/KWH)	Maintenance Costs	Chemical Costs	Total	KWHs/yr
Ultrafiltration	$35,357	$10,425	$40,970	$26,200	$3,220	---	---	$748,571
Liquid feed	---	---	---	---	398	$82,600	---	---
Accumulator	---	---	---	---	600	---	---	---
Chem. pump	---	---	---	35	---	---	---	1,000
Waste pump	---	---	---	1,730	---	---	---	49,429
Piping	---	---	154	---	197	---	---	---
Total	35,357	10,425	41,124	27,965	4,415	82,600	---	799,000
Supplemental O&M costs	---	---	---	---	1,348	---	---	---
Subtotal of direct O&M costs	---	---	---	---	---	---	$203,234	---
Administrative overhead#	---	---	---	---	---	---	40,647	---
Debt service and amortization**	---	---	---	---	---	---	157,793	---
Real estate taxes and insurance‡	---	---	---	---	---	---	15,364	---
Total first year operating costs	---	---	---	---	---	---	417,038	---

* Scale = 1,000 gpm.
† Mid-1978 dollars.
# At 20% of direct operating costs.
** At 10% interest over 7 years.
‡ At 2% of total capital.

(this compares to \$633,699 and \$871,016 for a reverse osmosis facility of the same capacity).

The change in total capital costs (exclusive of land costs) according to the scale of operation is shown in Figure 41. Within the range of 2,000 to 5,000 gpm, ultrafiltration demonstrates negative economies of scale (\$4.27 to \$4.86/1,000 gal). The capital cost at 1,000 gpm is equal to \$4.41/1,000 gal. The reason for this is the increasing costs associated with large scale implementation.

Ultrafiltration O&M requirements are shown in Figure 42. Labor costs demonstrate significant economies of scale, while maintenance and energy requirements are constant throughout the range.

The direct and indirect operating costs (including debt service and amortization) are used to calculate the average cost over the 7-year life cycle of the 1,000 gpm ultrafiltration facility. The life cycle average cost is \$3.02/1,000 gal (\$0.80/m^3). This compares to \$6.71 (\$1.77/m^3) for reverse osmosis. Figure 43 shows how the life cycle average costs fluctuate at five different scales of operation.

CHEMICAL OXIDATION/REDUCTION

Description

Oxidation/reduction, or "redox" reactions are those in which the operation state of at least one reactant is raised while that of another is lowered. In reaction (1) in alkaline solution:

$$(1)\quad 2MnO_4^- + CN^- + 2OH^- \qquad 2MnO_4^{2-} + CNO^- + H_2O$$

the oxidation state of the cyanide ion is raised from -1 to +1 (the cyanide is oxidized as it combines with an atom of oxygen to form cyanate); the oxidation state of the permanganate decreases from -1 to -2 (permanganate is reduced to manganate). This change in oxidation state implies that an electron was transferred from the cyanide ion to the permanganate. The increase in the positive valence (or decrease in the negative valence) with oxidation takes place simultaneously with reduction in chemically equivalent ratios. Figure 44 is a diagram of a cyanide destruction system.

Chemical reduction is of interest because metals can often be reduced to their elemental form for potential recycle or can be converted to less toxic oxidation states. One such metal is chromium, which, when present as chromium (VI), is a very toxic material. In the reduced state, chromium (III), the hazards are lessened and the chromium can be precipitated for removal.

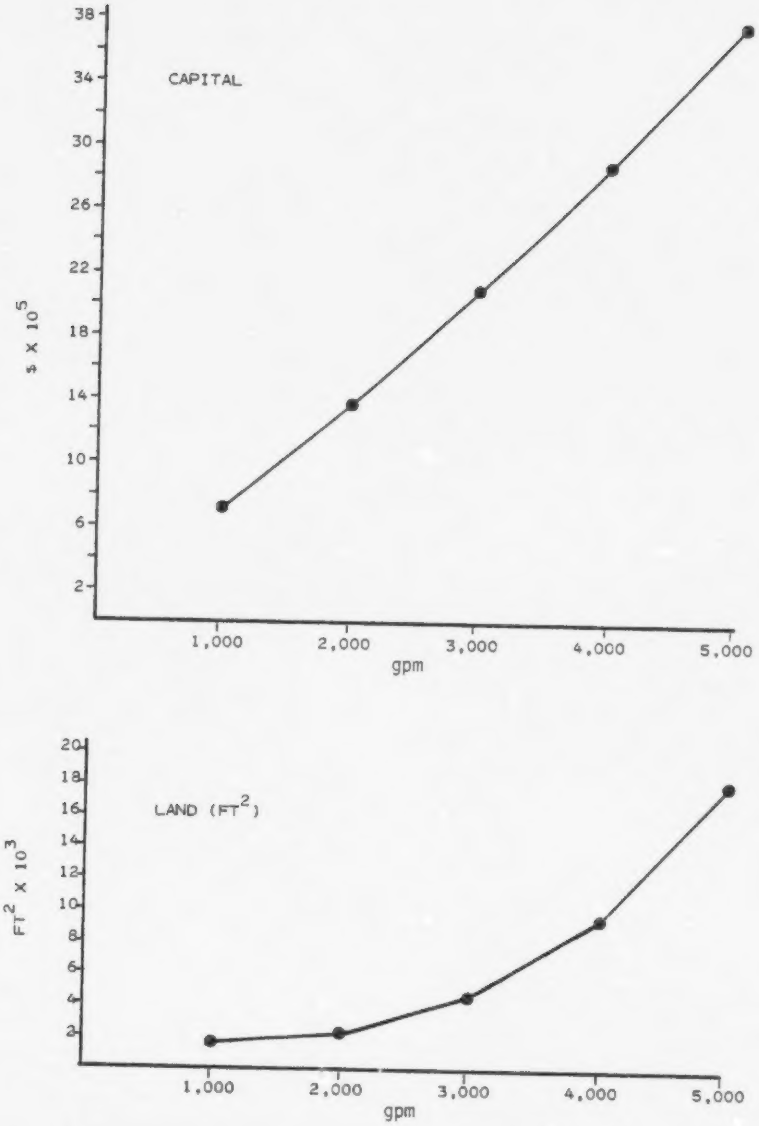

Figure 41. Ultrafiltration: changes in total capital costs with scale.

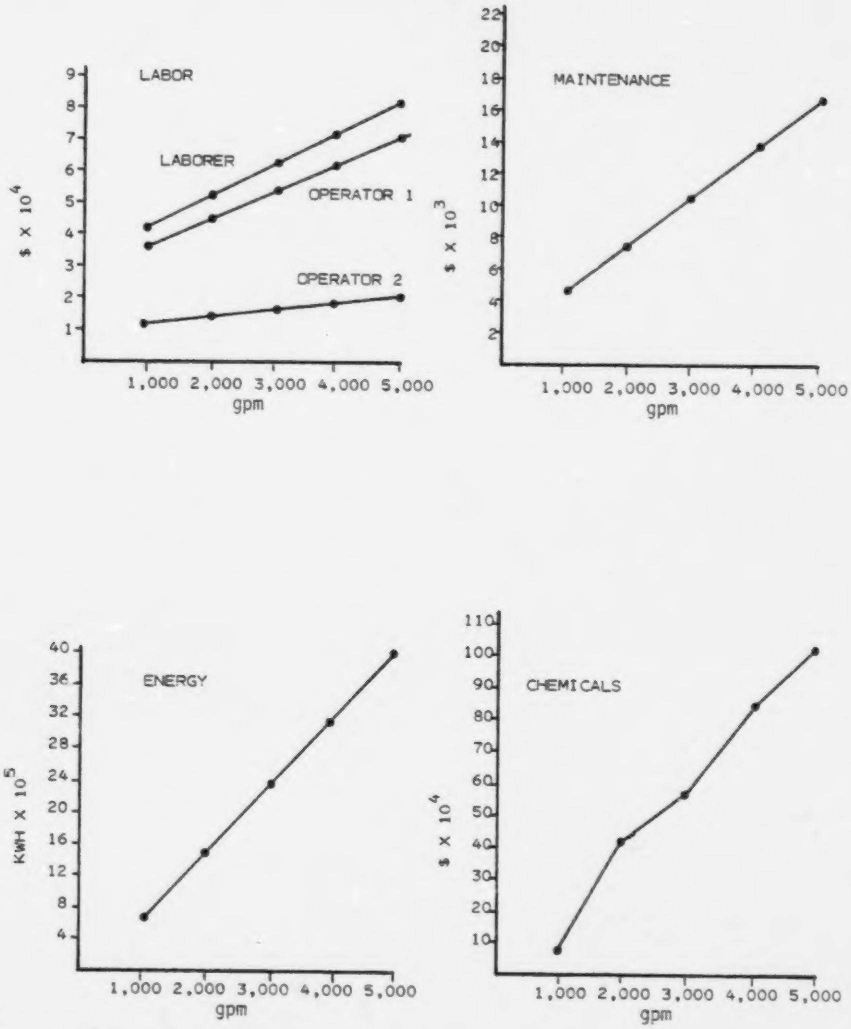

Figure 42. Ultrafiltration: changes in O&M requirements with scale.

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TABLE 33. COMPUTATION OF LIFE CYCLE AVERAGE COST FOR IMPLEMENTING ULTRAFILTRATION (LIFETIME - 7 YEARS)

Item	Direct Operating Costs*	Indirect Operating Costs†	Sum Operating Costs	Present Value Annualized Costs#	Annual Quantity of Throughput (x 1,000 Gal.)**
YEAR 1‡	$203,234	$213,804	$417,038	$417,035	124,800
YEAR 2	223,557	217,865	441,423	401,293	124,800
YEAR 3	245,913	222,336	468,250	386,983	124,800
YEAR 4	270,504	227,255	497,759	373,974	124,800
YEAR 5	297,555	232,655	530,220	362,147	124,800
YEAR 6	327,310	238,616	565,926	351,396	124,800
YEAR 7	360,041	245,162	605,204	341,622	124,800
TOTALS			3,525,817	2,634,450	873,600
Simple Average (Per 1,000 Gal.)			$4.04		
Simple Average (Per Cubic Meter)			$1.07		
Life Cycle Average (Per 1,000 Gal.)				$3.02	
Life Cycle Average (Per Cubic Meter)				$0.80	

---

* Assumes 10% annual inflation.

† Inflation increases the administrative overhead only.

# Assumes a 10% interest/discount rate to the beginning of the first year of operation.

** 1,000 GPM x 60 min x 8 hrs/day x 260 days/yr.

‡ First year costs in mid-1978 dollars - for Chicago example.

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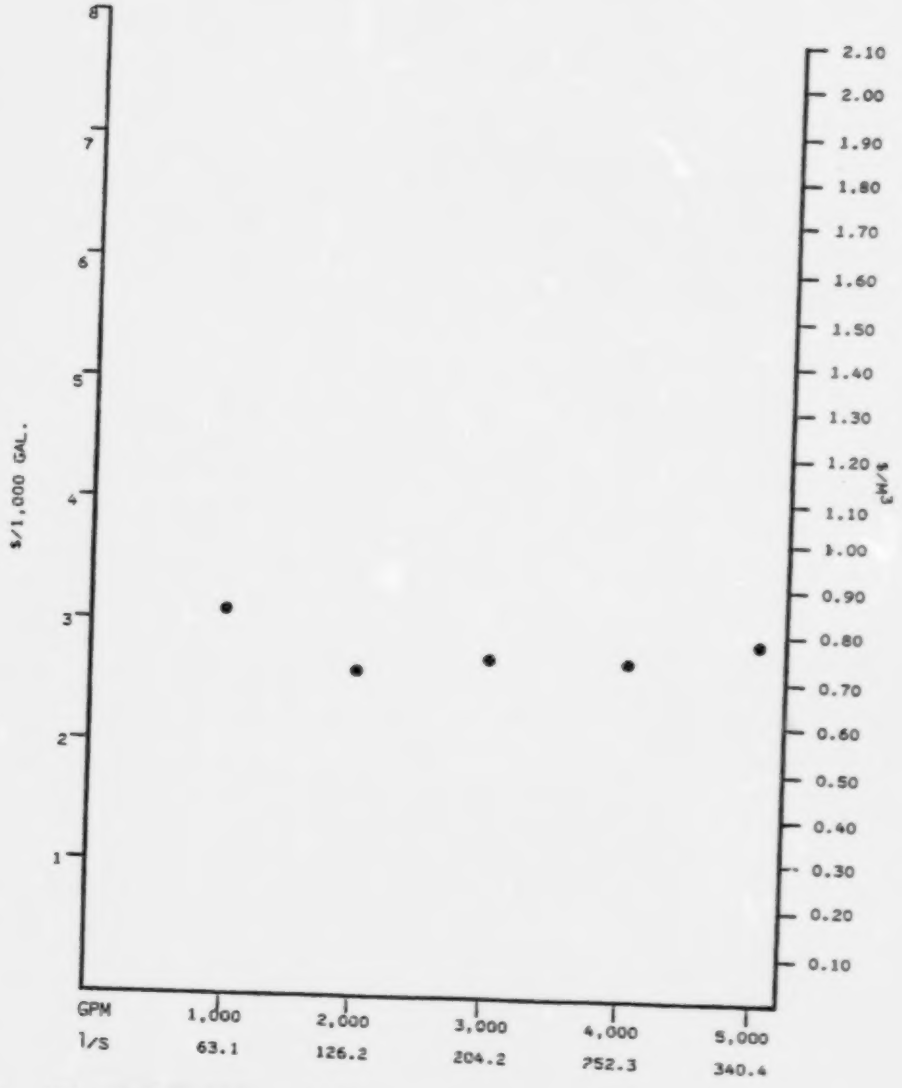

Figure 43. Ultrafiltration: life cycle costs at five scales of operation.

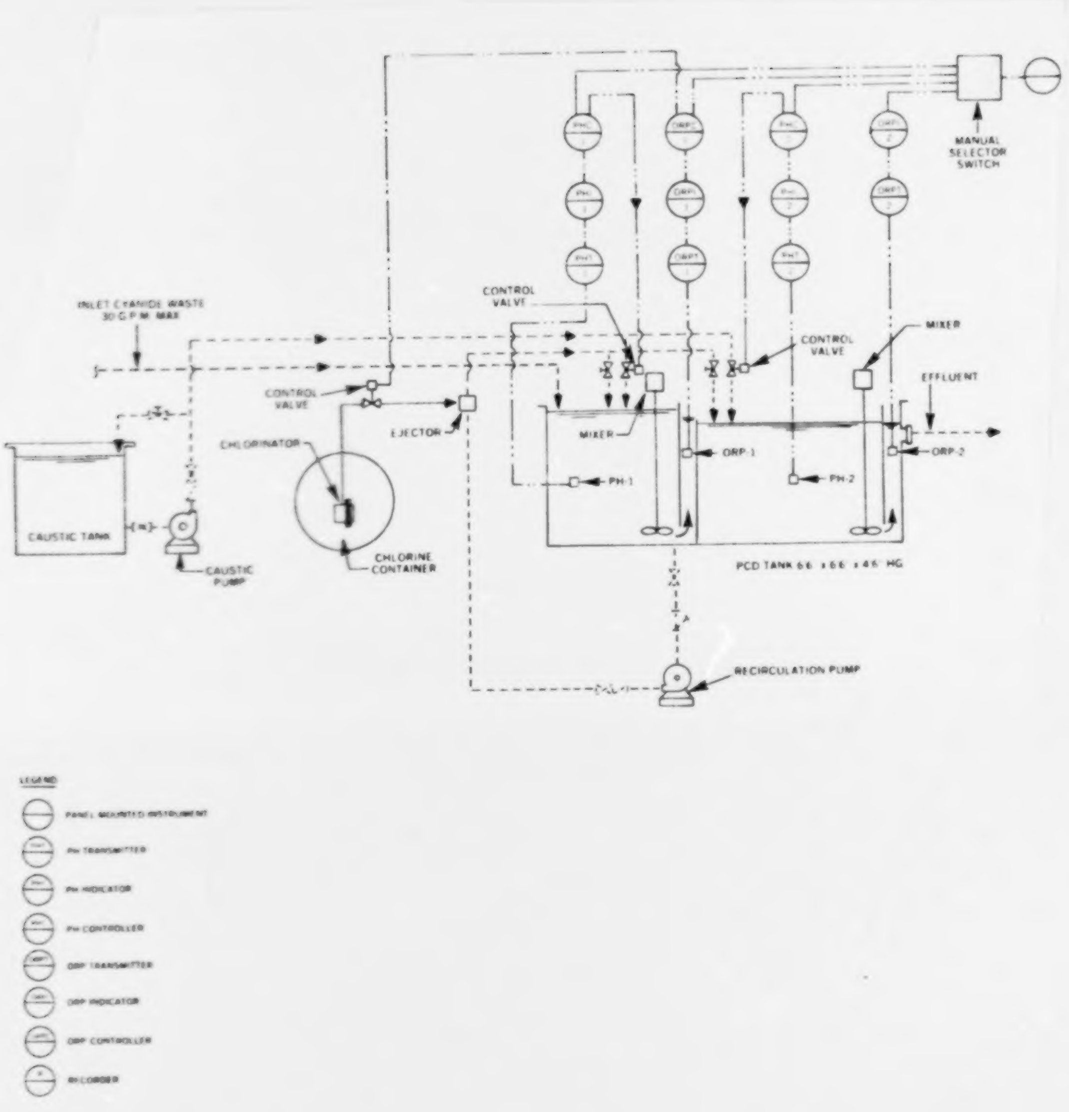
MANUAL SELECTOR SWITCH
INLET CYANIDE WASTE 30 G.P.M. MAX
CONTROL VALVE
CONTROL VALVE
CONTROL VALVE
MIXER
MIXER
EFFLUENT
EJECTOR
CHLORINATOR
CHLORINE CONTAINER
CAUSTIC TANK
CAUSTIC PUMP
ORP-1
ORP-2
PH-1
PH-2
PCD TANK 66 x 66 x 46 HG
RECIRCULATION PUMP
LEGEND
PANEL MOUNTED INSTRUMENT
PH TRANSMITTER
PH INDICATOR
PH CONTROLLER
ORP TRANSMITTER
ORP INDICATOR
ORP CONTROLLER
RECORDER

Figure 44. Flow diagram of PCD 1200 NG cyanide destruction system.

At the present time, chemical reduction is applied primarily to the control of hexavalent chromium in the plating and tanning industries and to the removal of mercury from caustic/chlorine electrolysis cell effluents. Figure 45 is a diagram of a chrome reduction system.

Fluorine is a powerful oxidizing agent. The other halogens, including chlorine, are also good oxidizing agents. The positive ions of noble metals are good oxidizing agents. Many of the oxygenated ions, such as Br_3^- and NO_3^- are strong oxidizing agents in acid solution. Certain sulfur compounds and base metals such as iron, aluminum, zinc and sodium are good reducing agents.

As shown in Figures 44 and 45, oxidation or reduction treatment systems are configured with mixing tanks, chemical storage and feed equipment (for gas, liquid or solid chemicals), pumps and piping.

The process modeled here is based on chemical oxidation as differentiated from thermal, electrolytic and biological oxidation. The oxidation reactions should be distinguished from the higher temperature and typically pressurized, wet oxidation processes, such as the Zimpro process, which are not included in this study.

Changes in Configuration with Scale

Additional reaction tanks are provided in order to treat increased flows. The maximum volume for a reactor in this model is 535 ft^3. Where flow rate and/or retention time necessitate larger reactor volume; multiple, equal-sized vessels are used.

Applications

Chemical oxidation/reduction is most commonly applied in the electroplating and metal finishing industry; as a treatment process for cyanide oxidation and chromium VI reduction. Chlorine dioxide and potassium permanganate have both been demonstrated in successful oxidation of a variety of pesticide compounds, including quat, paraquat and rotenone (6). Sodium borohydrate is a useful reducing agent for mercury, lead and silver-bearing wastes (14, 15).

Costs

Summaries of capital and first year operating costs for chemical oxidation/reduction are shown in Tables 34 and 35. These estimates are based on mid-1978 costs for components, unit processes, labor, utilities, etc., as applicable in Chicago, Illinois. The estimates are based on the cost files

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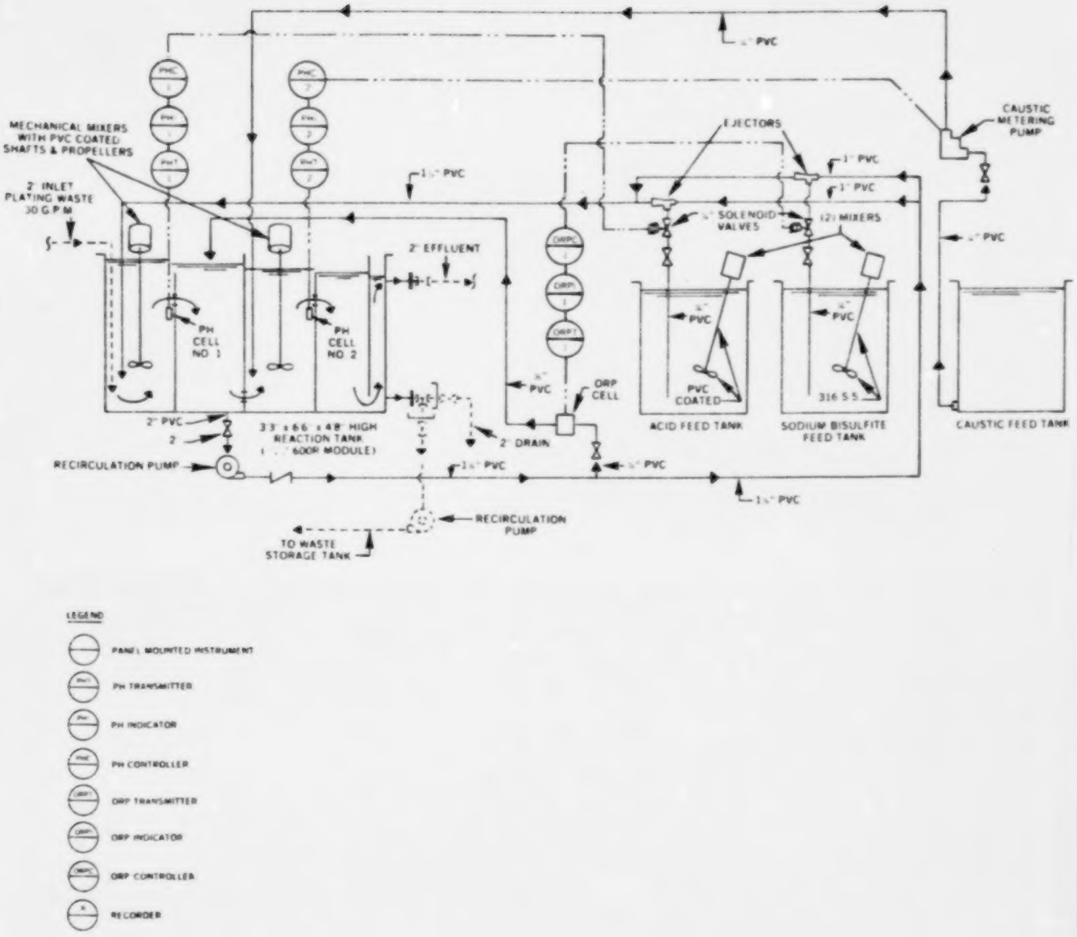
MECHANICAL MIXERS WITH PVC COATED SHAFTS & PROPELLERS
2" INLET PLATING WASTE 30 G.P.M.
PHC 1
PHI 1
PHT 1
PHC 2
PHI 2
PHT 2
1½" PVC
½" PVC
2" EFFLUENT
PH CELL NO. 1
PH CELL NO. 2
2" PVC
2
33" x 66" x 48" HIGH REACTION TANK
(600R MODULE)
RECIRCULATION PUMP
2" DRAIN
1½" PVC
RECIRCULATION PUMP
TO WASTE STORAGE TANK
½" PVC
ORPC 1
ORPI 1
ORPT 1
ORP CELL
EJECTORS
1" PVC
1" PVC
½" SOLENOID VALVES
(2) MIXERS
½" PVC
PVC COATED
316 S.S.
ACID FEED TANK
SODIUM BISULFITE FEED TANK
CAUSTIC METERING PUMP
CAUSTIC FEED TANK
1½" PVC
LEGEND
PANEL MOUNTED INSTRUMENT
PH TRANSMITTER
PH INDICATOR
PH CONTROLLER
ORP TRANSMITTER
ORP INDICATOR
ORP CONTROLLER
RECORDER

Figure 45. Chrome reduction system flow diagram.

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TABLE 34. SUMMARY OF CAPITAL COSTS FOR CHEMICAL OXIDATION/REDUCTION*

	Costs†						Quantities	
Capital Cost Category Module	Site Preparation	Structures	Mechanical Equipment	Electrical Equipment	Land	Total	Land (ft^2)	Other Storage Capacity (lbs)
Jacketed flash mixer	$ 99	$ 2,420	$ 90,500	$106	$ 978	---	$1,310	---
Gas storage/feed	432	39,851	10,810	---	4,290	---	5,760	$144,000
Liquid storage/feed	390	2,130	2,030	---	321	---	432	---
Solid storage/feed	1	20	19,432	---	5	---	10	---
Chem. pump	---	---	1,600	---	---	---	---	---
Chem. pump	---	---	1,600	---	---	---	---	---
Waste pump	---	---	2,950	---	---	---	---	---
Piping	450	---	24,600	---	---	---	---	---
Total	1,372	44,421	153,522	106	5,594	---	7,512	144,000
Supplemental capital costs	---	97,324#	---	---	---	---	---	---
Subtotal of capital costs	---	---	---	---	---	$302,339	---	---
Working capital**	---	---	---	---	---	32,033	---	---
AFDC‡	---	---	---	---	---	15,117	---	---
Grand total of capital costs	---	---	---	---	---	349,489	---	---

* Scale = 1,000 gpm.

† Mid-1978 dollars.

# Building.

** At one month of direct operating costs.

‡ Allowance for funds during construction at 5% of capital costs.

TABLE 35. SUMMARY OF FIRST YEAR O&M COSTS FOR CHEMICAL OXIDATION/REDUCTION*

	Costs†							Quantities	
	Labor								
O&M Cost Category Module	Type 1 Operator 1 ($7.77/hr)	Type 2 Operator 2 ($9.19/hr)	Type 3 Laborer ($6.76/hr)	Energy Electrical ($0.035/KWH)	Maintenance Costs	Chemical Costs	Total	KWH (yr)	Other Gas (lbs/yr)
Jacketed flash mixer	$357	$ 277	$10,060	$ 598	$4,530	---	---	$17,085	---
Gas storage/feed	12	1,392	93	---	108	$362,000	---	---	1.25×10^6
Liquid feed	---	---	---	---	398	175	---	---	---
Solid feed	88	100	100	---	500	300	---	---	---
Chem. pump	---	---	---	52	---	---	---	1,486	---
Chem. pump	---	---	---	52	---	---	---	1,486	---
Waste pump	---	---	---	1,730	---	---	---	49,429	---
Piping	---	---	128	---	123	---	---	---	---
Total	457	1,769	10,381	2,432	5,659	362,475	---	69,486	---
Supplemental O&M costs	---	---	---	---	1,348	---	---	---	---
Subtotal of direct O&M costs	---	---	---	---	---	---	$384,521	---	---
Administrative overhead#	---	---	---	---	---	---	76,904	---	---
Debt service and amortization**	---	---	---	---	---	---	92,194	---	---
Real estate taxes and insurance‡	---	---	---	---	---	---	6,990	---	---
Total first year operating costs	---	---	---	---	---	---	560,609	---	---

* Scale = 1,000 gpm.

† Mid-1978 dollars.

# At 20% of direct operating costs.

** At 10% interest over 5 years.

‡ At 2% of total capital.

in Appendices B and C and the cost equations included in Appendix F.

As shown in Table 34, the most costly unit process is the jacketed flash mixer. The chemical storage and feed equipment, together with the facility piping, comprise more than 30 percent of the subtotal capital costs. Since removal of constituents as sludges is not an objective of this treatment technology, sludge handling and dewatering processes are not included. As expected, the major operating cost is for chemical addition.

Figure 46 shows the capital costs (exclusive of land costs) for five scales of operation and the corresponding land area requirements. The capital costs demonstrate significant economies of scale; particularly within the range between 1,000 and 3,000 gpm. The capital costs at those capacities are equal to \$2.38 and \$1.13, respectively. The savings incurred at these smaller scales of operation are attributed to the ability to use a single reactor (flashmixer) for increasing flow rates. Above 3,000 gpm, multiple vessels are used; increasing the need for supplementary structures and equipment, and partially offsetting the economies of scale at the larger operating capacities.

The O&M requirements for chemical oxidation/reduction as a function of scale are shown in Figure 47. Labor and maintenance show economies of scale, while the electrical demand (0.56 kwh/1,000 gal) is constant at all capacities. The chemical costs increase substantially at the larger scales of operation (\$2.90 versus \$11.39 per 1,000 gal treated at 1,000 and 50,000 gpm, respectively). The increase in chemical demand is due to less efficient chemical contact in the large scale facilities.

HYDROLYSIS

Description

The term hydrolysis applies generally to reactions in which water brings about a double decomposition, with hydrogen going to one component and hydroxyl to the other (6). The general formula is $XY + H_2O \rightarrow HY + XOH$; examples from organic and inorganic chemistry are respectively:

$$C_5H_{11} + H_2O \rightarrow HCl + C_5H_{11}OH \text{ and}$$

$$KCN + H_2O + NaOH \rightarrow HCN + KOH$$

In general it is necessary for a bond between two atoms to be broken in hydrolysis, but the term is sometimes used for reactions in which one bond of multiple bond is broken, as in the nitrile example.

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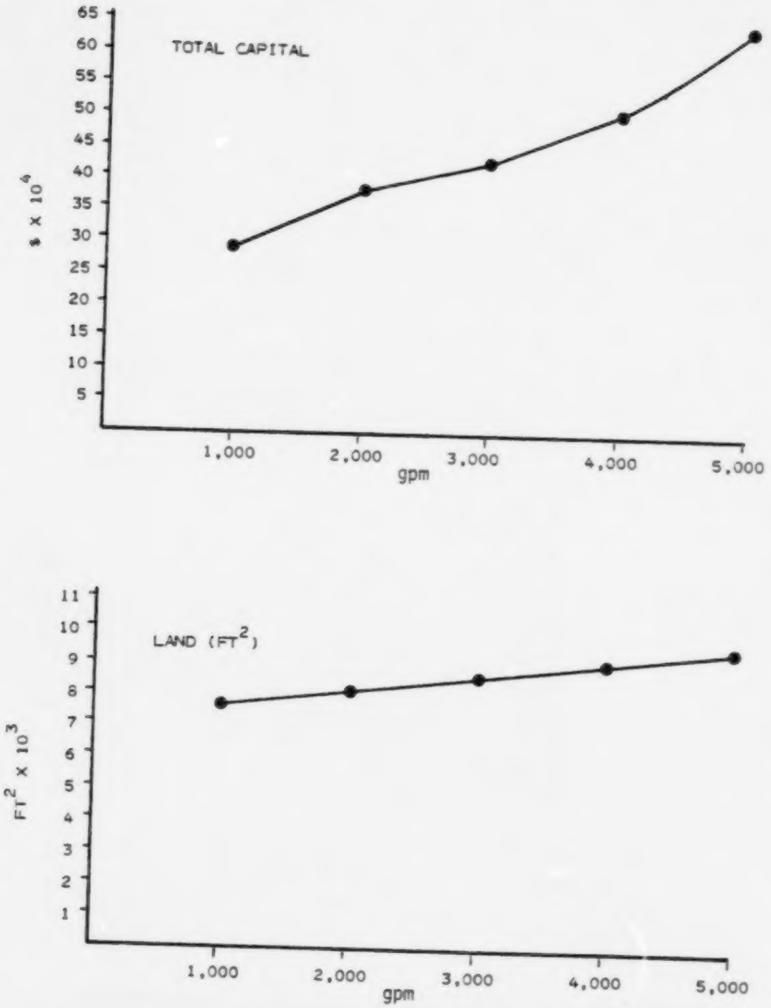

Figure 46. Chemical/oxidation reduction: changes in total capital costs with scale.

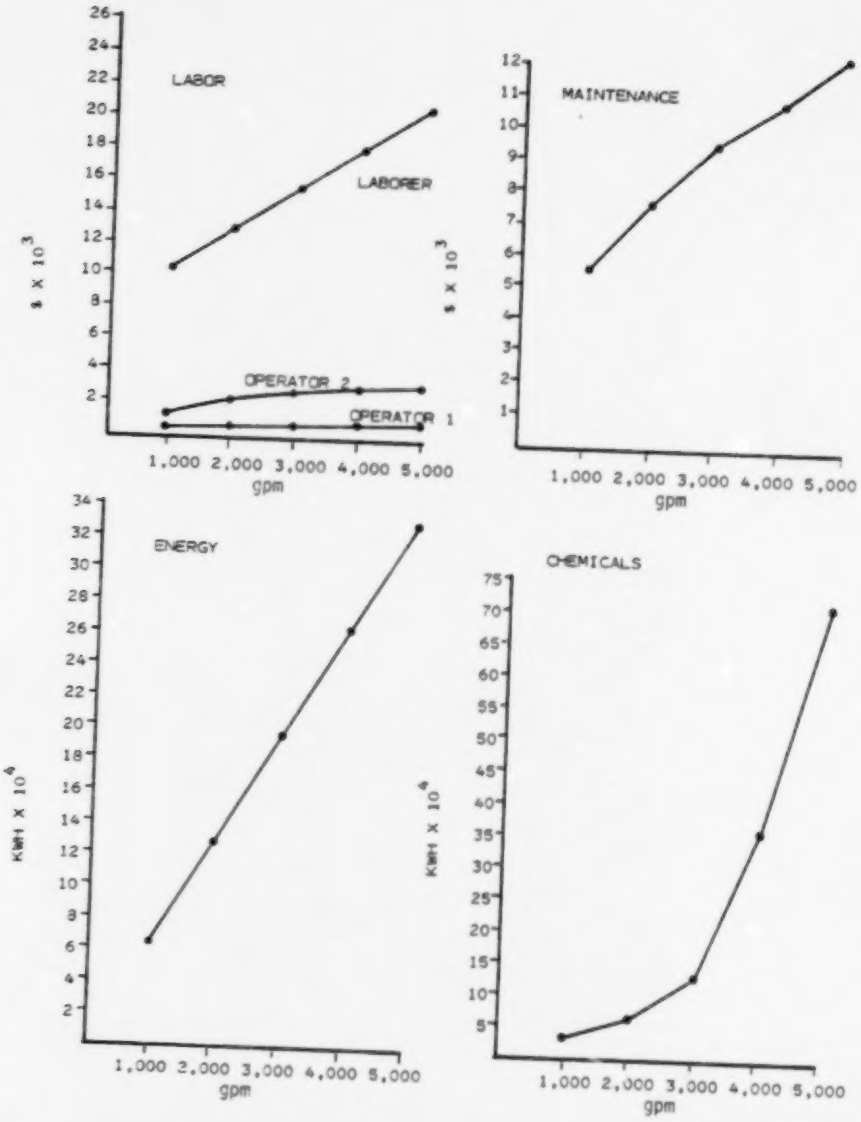

Figure 47. Chemical oxidation/reduction: changes in O&M requirements with scale.

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TABLE 36. COMPUTATION OF LIFE CYCLE AVERAGE COST FOR IMPLEMENTING CHEMICAL OXIDATION/REDUCTION (LIFETIME - 5 YEARS)

Item	Direct Operating Costs*	Indirect Operating Costs†	Sum Operating Costs	Present Value Annualized Costs#	Annual Quantity of Throughput (x 1,000 Gal.)**
YEAR 1‡	$384,521	$176,088	$560,609	$560,609	124,800
YEAR 2	422,973	183,778	606,751	551,597	124,800
YEAR 3	465,270	192,238	657,508	543,365	124,800
YEAR 4	511,797	201,543	713,340	535,932	124,800
YEAR 5	562,977	211,779	774,756	529,158	124,800
TOTALS			3,312,964	2,720,661	624,000
Simple Average (Per 1,000 Gal.)			$5.31		
Simple Average (Per Cubic Meter)			$1.40		
Life Cycle Average (Per 1,000 Gal.)				$4.36	
Life Cycle Average (Per Cubic Meter)				$1.15	

1.15

---

* Assumes a 10% annual inflation.

† Inflation increases the administrative overhead only.

# Assumes a 10% interest/discount rate to the beginning of the first year of operation.

** 1,000 GPM x 60 min x 8 hrs/day x 260 days/yr.

‡ First year costs in mid-1978 dollars - for Chicago example.

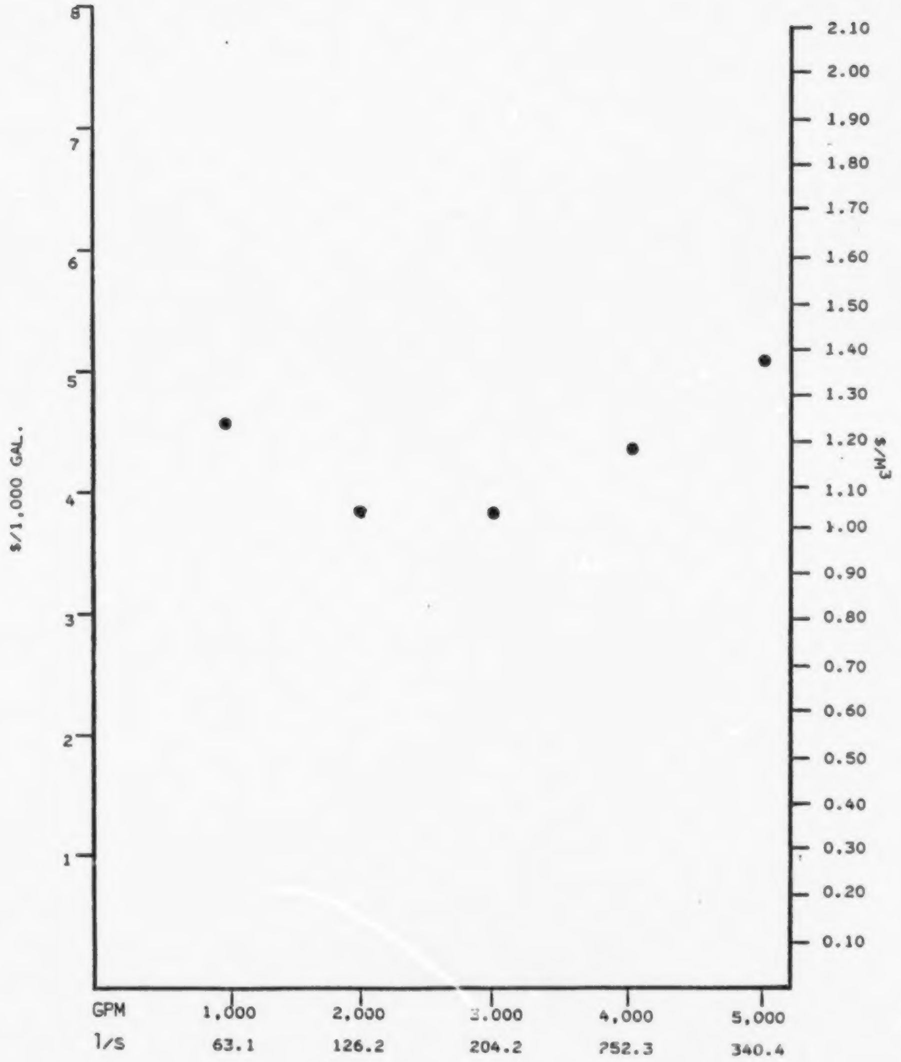

Figure 48. Chemical oxidation/reduction: life cycle costs at five scales of operation.

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Inorganic hydrolytic reactions, in which a salt reacts with water to form acid and base, are usually the reverse of neutralization. The trivalent metal salts of aluminum and iron undergo a different mechanism of hydrolysis; during a series of reactions with water, various multivalent hydrous oxides (6) are formed. These charged species are important in the floc formation and the treatment of turbid waters by precipitation.

Organic hydrolysis may include reactions in which water is not a reactant. For example, the addition of an alkali to solution and the subsequent formation of the alkali salt of an organic acid is described as hydrolysis. Although water by itself can bring about hydrolysis, most commercial processes employ elevated temperatures and pressures to promote reaction. Acids, alkalies and enzymes are commonly used as catalysts, although an alkali can also frequently participate as a stoichiometric reactant.

The agents for acid hydrolysis most commonly used are hydrochloric and sulfuric acids, but many others are of potential use (formic, oxalic, benzenesulfonic, etc.). Alkaline hydrolysis utilizes sodium hydroxide most frequently, but the alkali carbonates as well as appropriate potassium, calcium, magnesium and ammonium compounds can be applied.

The model costed herein is based on the Twitchell process (16, 17). This is the traditional method for producing fatty acids in a batch. The basis of the process is to process the fat in the presence of a hydrolyzing reagent and heat, and then to separate products. The system consists of a waste deaerator, chemical feed and storage, flash mixers, a decanter, storage tanks and a variety of pumps (gravity flow is used wherever possible). Figure 49 shows the configuration of equipment.

Changes in Configuration with Scale

Additional tanks are used as the batch volume increases. The maximum volume for a tank is 535 ft^3. Where flow rate and/or retention time necessitates additional reactor volume, equal sized parallel units are employed.

Applications

The following applications of hydrolysis are documented:

The Organic Chemicals Industry--

Sludge from the acid treatment of organic wastes is often hydrolyzed yielding recoverable byproducts.

The Pesticides Industry--

Many pesticides are subject to deterioration in acid or most often alkaline media. Carbamates and organophosphorous

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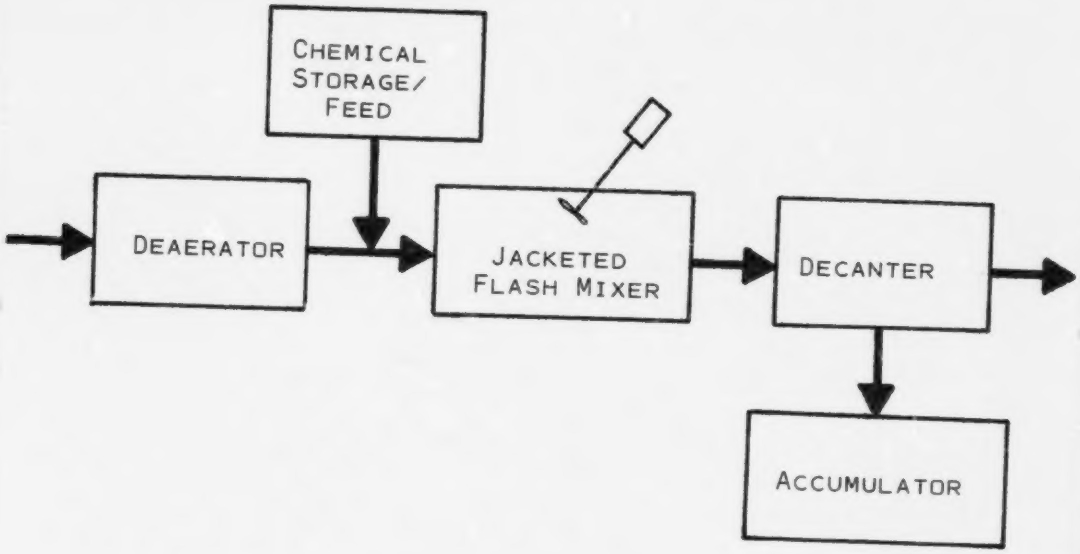
CHEMICAL STORAGE/ FEED
DEAERATOR
JACKETED FLASH MIXER
DECANTER
ACCUMULATOR

Figure 49. Flow diagram of the hydrolysis reactor and associated modules.

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compounds can be hydrolyzed under the correct temperature and pH conditions. One organophosphate plant uses an enclosed glass-lined reaction vessel to hydrolyze waste. One part of 20 percent caustic solution and 30 parts of waste are hydrolyzed in a batch at 98° C for 15 hours. Another manufacturer suggests the use of an aqueous caustic soda and detergent solution to decontaminate containers and dispose of pesticide residues.

Costs

Capital and first year operating costs are calculated for hydrolysis (Tables 37 and 38). The most costly element is the deaerator unit and associated structures ($923,910 at 5,000 gpm). The total capital costs for the Chicago-based example are $1,496,229. Major operating costs are for maintenance of the deaerator and jacketed flash mixer. The total first year operating costs are $466,345.

Figure 50 shows the capital costs (excluding land costs) at five scales of operation for the technology. The accompanying graph shows the land area requirements at the same scales of operation. The capital cost data indicates that there are significant economies of scale from 1,000 gpm ($2.54/1,000 gal treated) to 3,000 gpm ($2.06/1,000 gal). The costs then increase to $2.11 and $2.20/1,000 gal at 4,000 and 5,000 gpm, respectively. As in the case of chemical oxidation/reduction, hydrolysis capital expenses are impacted by the need for multiple, parallel reactors at larger plant capacities.

Figure 51 shows the fluctuation in O&M requirements with scale for the model facility (operating 8 hr/day and 260 day/yr). Total labor costs are low ($10,092 at 5,000 gpm) and reflect the minimal supervision and servicing necessary to operate the technology. Maintenance costs demonstrate marked economy of scale; and energy demands are fairly constant over the range studied (0.22 kwh/1,000 gal). Chemical costs are minimal. Added chemicals serve as catalysts only.

The average costs of the Chicago-based model facility, over a life cycle of 5 years, are calculated in Table 39. The life cycle average cost is $0.63/1,000 gal ($0.17/m^3) for the 5,000 gpm facility. Figure 52 shows the variation in the average cost with scale. The reduction in capital unit costs at the smaller scales of operation (1,000 to 3,000 gpm) is reflected in the life cycle calculations.

AERATED LAGOON

Description

An aerated lagoon is a basin in which wastewater is treated on a flow-through basis. Oxygen is usually supplied by means of

TABLE 37. SUMMARY OF CAPITAL COSTS FOR HYDROLYSIS*

Capital Cost Category Module	Costs† Site Preparation	Structures	Mechanical Equipment	Electrical Equipment	Land	Total	Quantities Other Land (ft^2)
Deaerator	$ 4,290	$384,000	$539,910	---	$42,600	---	$52,257
Jacketed flash mixer	134	3,580	20,400	$518	1,330	---	1,790
Decanter	66	2,590	32,810	---	659	---	885
Accumulator	8,330	107,000	38,600	---	6,220	---	8,362
Liquid chem. feed	586	4,270	2,590	---	400	---	636
Chem. pump	---	---	1,730	---	---	---	---
Chem. pump	---	---	1,730	---	---	---	---
Waste pump	---	---	2,950	---	---	---	---
Piping	1,125	---	72,500	---	---	---	---
Total	14,531	501,440	713,220	518	51,209	---	63,930
Supplemental capital costs	---	141,303#	---	---	---	---	---
Subtotal of capital costs	---	---	---	---	---	$1,422,221	---
Working capital**	---	---	---	---	---	2,897	---
AFDC‡	---	---	---	---	---	71,111	---
Grand total of capital costs	---	---	---	---	---	1,496,229	---

* Scale = 5,000 gpm.
† Mid-1978 dollars.
# Building.
** At one month of direct operating costs.
‡ Allowance for funds during construction at 5% of capital costs.

TABLE 38. SUMMARY OF FIRST YEAR O&M COSTS FOR HYDROLYSIS*

O&M Cost Category Module	Costs† Labor Type 1 Operator 1 ($7.77/hr)	Type 2 Operator 2 ($9.19/hr)	Type 3 Laborer ($6.76/hr)	Energy Electrical ($0.035/KWH)	Maintenance Costs	Chemical Costs	Total	Quantities Other KWHs/yr
Deaerator	$ 78	$ 92	$1,224	---	$ 5,399	---	---	---
Jacketed flash mixer	235	185	6,679	$2,990	10,200	---	---	$ 85,429
Decanter	78	92	1,225	---	501	---	---	---
Accumulator	---	---	---	---	800	---	---	---
Chem. feed	---	---	---	---	400	$349	---	---
Chem. pump	---	---	---	86	---	---	---	2,457
Chem. pump	---	---	---	86	---	---	---	2,457
Waste pump	---	---	---	1,730	---	---	---	49,429
Piping	---	---	204	---	363	---	---	---
Total	391	369	9,332	4,892	17,663	349	---	139,772
Supplemental O&M costs	---	---	---	---	1,770	---	---	---
Subtotal of direct O&M costs	---	---	---	---	---	---	$ 34,766	---
Administrative overhead#	---	---	---	---	---	---	6,953	---
Debt service and amortization**	---	---	---	---	---	---	394,701	---
Real estate taxes and insurance‡	---	---	---	---	---	---	29,925	---
Total first year operating costs	---	---	---	---	---	---	466,345	---

* Scale = 5,000 gpm.

† Mid-1978 dollars.

# At 20% of direct operating costs.

** At 10% interest over 5 years.

‡ At 2% of total capital.

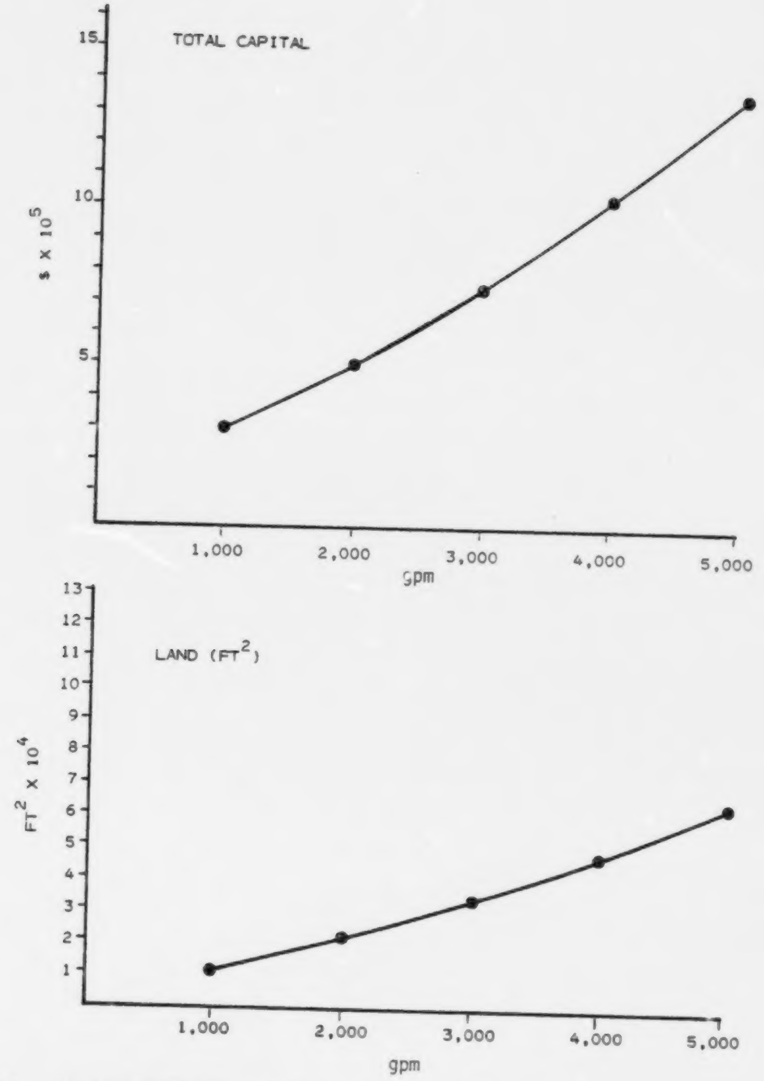

Figure 50. Hydrolysis: changes in total capital costs with scale.

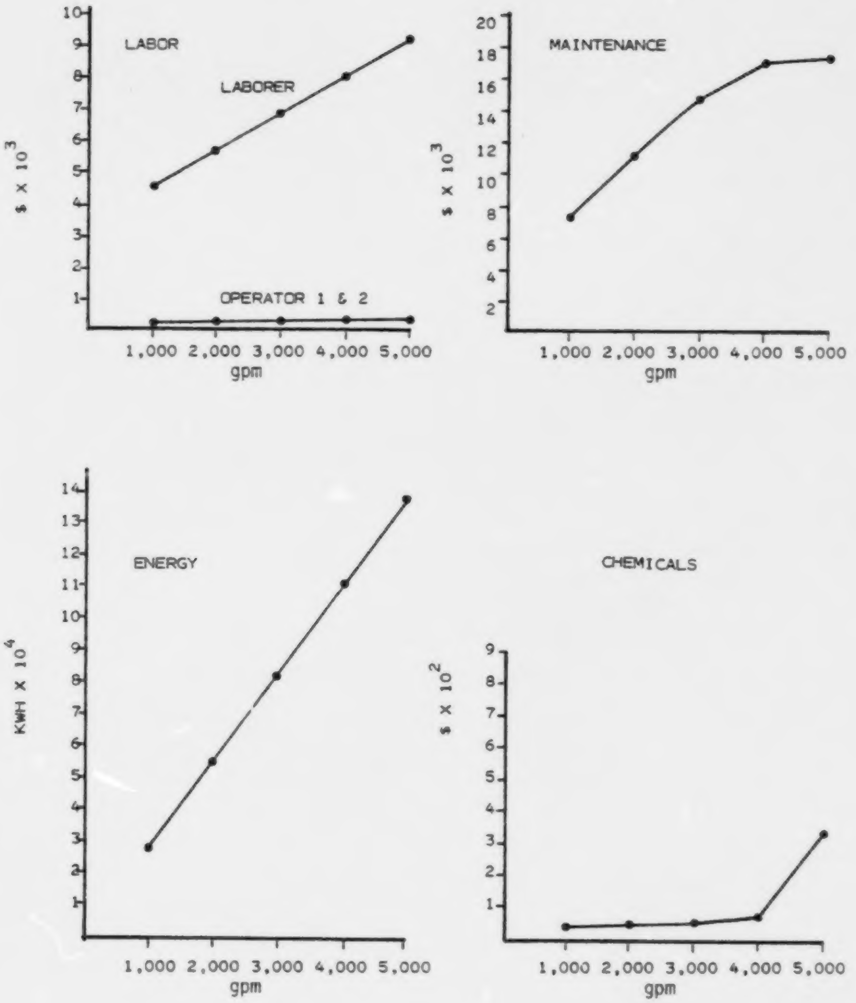

Figure 51. Hydrolysis: changes in O&M requirements with scale.

TABLE 39. COMPUTATION OF LIFE CYCLE AVERAGE COST FOR IMPLEMENTING HYDROLYSIS (LIFETIME - 5 YEARS)

Item	Direct Operating Costs*	Indirect Operating Costs†	Sum Operating Costs	Present Value Annualized Costs#	Annual Quantity of Throughput (x 1,000 Gal.)**
YEAR 1‡	$34,766	$431,579	$466,345	$466,345	624,000
YEAR 2	38,243	432,275	470,517	427,743	624,000
YEAR 3	42,067	433,039	475,106	392,650	624,000
YEAR 4	46,274	433,881	480,154	360,747	624,000
YEAR 5	50,901	434,806	485,707	331,745	624,000
TOTALS			2,377,829	1,979,230	3,120,000
Simple Average (Per 1,000 Gal.)			$0.76		
Simple Average (Per Cubic Meter)			$0.20		
Life Cycle Average (Per 1,000 Gal.)				$0.63	
Life Cycle Average (Per Cubic Meter)				$0.17	

* Assumes 10% annual inflation.

† Inflation increases the administrative overhead only.

# Assumes a 10% interest/discount rate to the beginning of the first year of operation.

** 5,000 GPM x 60 min x 8 hrs/day x 260 days/yr.

‡ First year costs in mid-1978 dollars - for Chicago example.

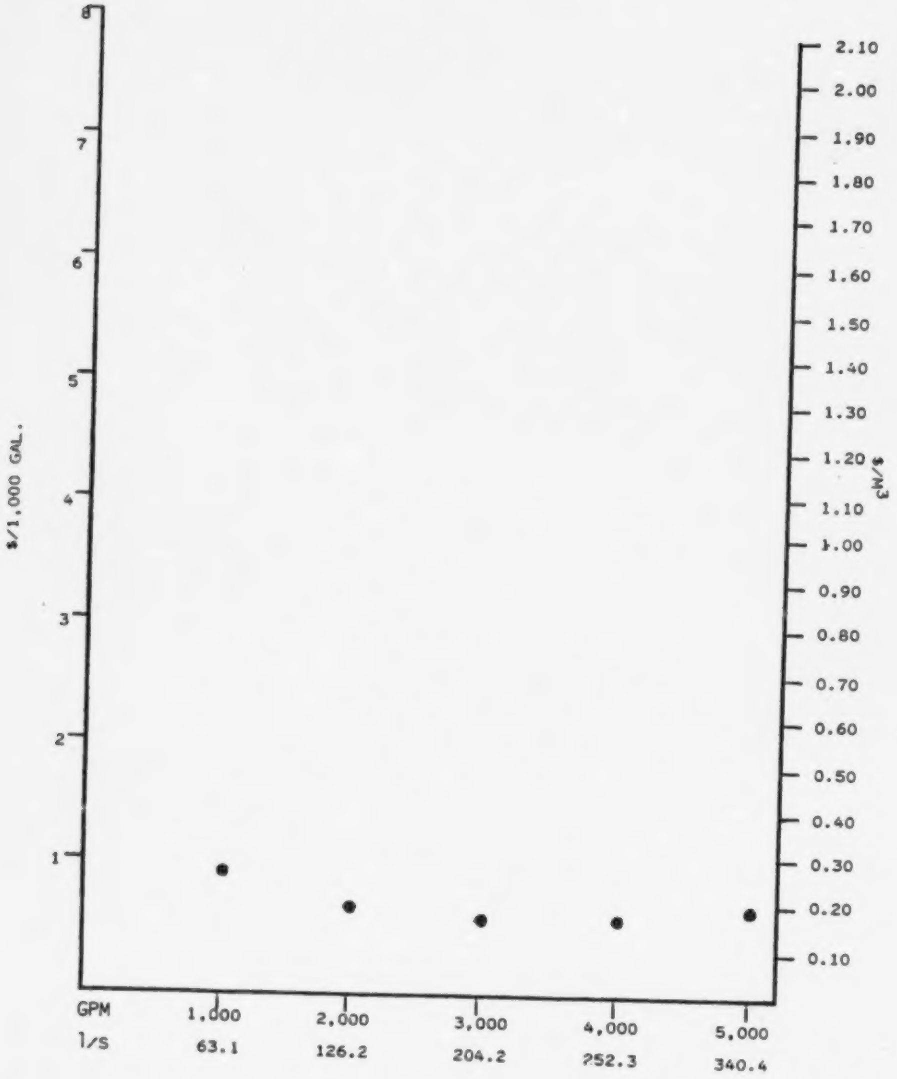

Figure 52. Hydrolysis: life cycle costs at five scales of operation.

surface aerators or diffused aeraton units. The action of the aerators is used to keep the contents of the basin in suspension. Depending on the amount of mixing, lagoons are often classified as either aerobic or aerobic-anaerobic.

The contents of an aerobic lagoon are completely mixed and neither the incoming solids nor the biological solids products from waste conversion are allowed to settle out (Figure 53) In effect, the essential function of this type of lagoon is waste conversion to biological solids. Depending on the detention time, the effluent will contain about a third to half the value of the incoming biological oxygen demand (BOD) in the form of cell tissue. Before the effluent can be discharged, however, the solids must be removed by settling (a settling tank is a normal component of most lagoon systems).

Factors that must be considered in the process design of aerated lagoons include: (1) required BOD reduction, (2) effluent characteristics, (3) oxygen requirements, (4) temperature effects, and (5) energy requirement for mixing.

Changes in Configuration with Scale

The model calculations included in Appendix F assume that single lagoon is used for all foreseen volumes. The assumed lagoon depth is 12 ft. Retention time is based on the anticipated degradation rate according to the first order removal:

$$\frac{S}{So} = \frac{1}{1 + K(v/Q)}$$

where

S = effluent $BOD_5 mg/\ell$

So = influent $BOD_5 mg/\ell$

K = removal rate constant, day^{-1}

V = volume (million gallons)

Q = flow, mgd

Applications

The primary objective of the aerated lagoon is the conversion of biodegradable organic compounds into cell mass. Organic constituents in the organic chemical and pesticide industry waste streams, that are not biocidal or resistant to degradation, can be treated with sufficient retention time (Appendix E).

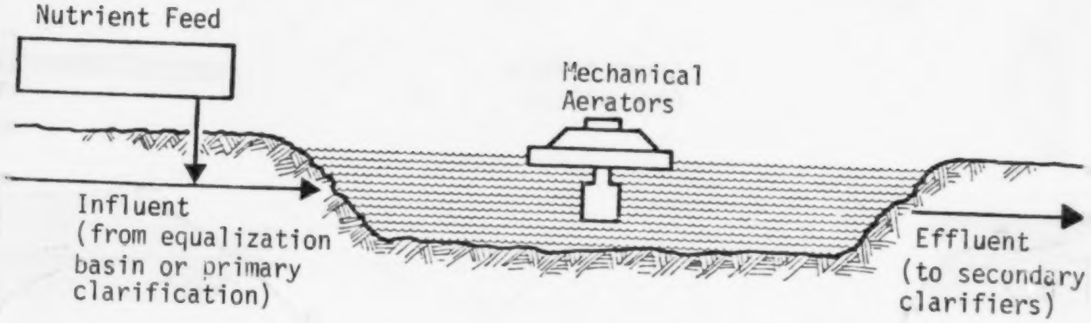
Nutrient Feed
Mechanical Aerators
Influent (from equalization basin or primary clarification)
Effluent (to secondary clarifiers)

Figure 53. Aerated lagoon.

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Costs

Capital costs for aerated lagoon are itemized in Table 40. The most costly unit processes are the sedimentation basin (used for primary clarification) and the sludge dewatering equipment. The total capital cost for a 5,000 gpm Chicago-based facility is $4,579,421 (mid-1978 dollars).

Table 41 summarizes the first year operating costs. Almost 45 percent of the direct O&M costs are attributable to the requirements for nutrient addition to supplement nitrogen and phosphorus-deficient industrial wastewaters. The total first year operating costs, including administrative overhead ($159,062), debt service and amortization ($602,074) and real estate taxes and insurance ($91,588) are $1,648,036.

Figure 54 shows the capital costs (excluding land costs) for five scales of operation and the corresponding land requirements for aerated lagoon. The capital costs per 1,000 gallons of waste treated decrease from $7.59 at 1,000 gpm to $5.04 at 3,000 gpm. The costs then increase to $6.08 and $6.63 at 4,000 and 5,000 gpm, respectively. The costs for chemical storage and feed equipment, as well as sludge dewatering facilities, increase substantially at the larger plant capacities. It is likely that less expensive, large-volume sludge dewatering techniques would significantly reduce the capital costs for these installations.

The O&M requirements for aerated lagoon as a function of scale are shown in Figure 55. Total labor costs are $118,742 and $236,670 at 1,000 and 5,000 gpm, respectively. A significant portion of these costs are attributable to the requirement for laborers to operate and service the numerous unit processes comprising the technology. Maintenance and energy demands are fairly constant over the range studied and chemical costs increase with increased capacity.

The average cost of the example facility, over a life cycle of 15 years, is calculated in Table 42. The life cycle average cost for the 5,000 gpm facility is $2.15/1,000 gal ($0.57/m^3). Figure 56 shows the life cycle average cost at five scales of operation. The analysis shows the fluctuations in capital costs and increases in chemical costs at the larger scales of operation.

TRICKLING FILTER

Description

Trickling filters are another biological treatment option for degradation of dilute, non-biocidal, organic waste streams (Figure 57). The filter media, comprised of crushed rock, slag, stone or manufactured plastic elements provides a surface

TABLE 40. SUMMARY OF CAPITAL COSTS FOR AERATED LAGOON*

Capital Cost Category Module	Costs†							Quantities	
	Site Preparation	Structures	Mechanical Equipment	Electrical Equipment	Land	Other	Total	Land (ft^2)	Other Excavation
Aerated lagoon	$182,000	$ 2,830	$ 252,000	---	$122,000	$34,500	---	$164,000	$23,900
Chemical feed	14,710	213,000	935,000	---	6,220	---	---	8,362	---
Chemical feed	8,330	107,000	29,500	---	1,520	---	---	2,039	---
Waste pump	---	---	10,800	---	---	---	---	---	---
Chem. pump	---	---	1,530	---	---	---	---	---	---
Chem. pump	---	---	1,470	---	---	---	---	---	---
Sludge dewatering	178	42,600	919,000	$ 9,190	4,120	---	---	5,530	---
Yard piping	900	---	55,200	---	---	---	---	---	---
Sedimentation basin	29,700	241,000	766,000	2,020	25,500	---	---	34,300	---
Clarifier	995	115,000	22,300	172	645	---	---	867	---
Total	236,813	721,430	2,992,800	11,382	160,005	34,500	---	215,098	23.900
Supplemental capital costs	---	141,303#	---	---	---	---	---	---	---
Subtotal of capital costs	---	---	---	---	---	---	$4,298,233	---	---
Working capital**	---	---	---	---	---	---	66,276	---	---
AFDC‡	---	---	---	---	---	---	214,912	---	---
Grand total of capital costs	---	---	---	---	---	---	4,579,421	---	---

* Scale = 5,000 gpm; 70% efficiency (BOD removal); BOD - 100 ppm; total nitrogen = 4.0 ppm; total phosphorus = 1.0 ppm K = 5.0 day-1.

† Mid-1978 dollars.

# Building.

** At one month of direct operating costs.

‡ Allowance for funds during construction at 5% of capital costs.

TABLE 41. SUMMARY OF FIRST YEAR O&M COSTS FOR AERATED LAGOON*

	Costs†							
	Labor							
O&M Cost Category Module	Type 1 Operator 1 ($7.77/hr)	Type 2 Operator 2 ($9.19/hr)	Type 3 Laborer ($6.76/hr)	Energy Electrical ($0.035/KWH)	Maintenance Costs	Chemical Costs	Total	Other KWH (yr)
Aerated Lagoon	14,094	3,327	134,838	24,300	12,600	---	---	694,285
Chemical feed	---	---	---	---	900	349,000	---	---
Chemical feed	---	---	---	---	800	1,750	---	---
Waste pump	---	---	---	8,630	---	---	---	246,571
Chemical pump	---	---	---	35	---	---	---	1,000
Chemical pump	---	---	---	17	---	---	---	486
Yard piping	---	---	179	---	276	---	---	---
Sedimentation basin	3,911	277	4,085	102	76,600	---	---	2,914
Clarifier	14,181	1,007	14,810	102	---	---	---	2,914
Sludge dewatering	3,911	1,200	40,850	70,500	9,240	2,020	---	2,014,286
Total	36,097	5,811	194,762	103,686	100,416	352,770	---	2.96×10^6
Supplemental O&M Costs	---	---	---	---	1,770	---	---	---
Subtotal of direct O&M costs	---	---	---	---	---	---	795,312	---
Administrative overhead#	---	---	---	---	---	---	159,062	---
Debt service and amortization **	---	---	---	---	---	---	602,074	---
Real estate taxes and insurance ‡	---	---	---	---	---	---	91,588	---
Total first year operating costs	---	---	---	---	---	---	1,648,036	---

* Scale = 5,000 gpm; 70% efficiency (BOD removal); BOD=100 ppm, total nitrogen=4.0 ppm;total phosphorus=1.0 ppm;$K=5.0 day^{-1}$.
† Mid-1978 dollars.
# At 20% of direct operating costs.
** At 10% interest over 15 years.
‡ At 2% of total capital.

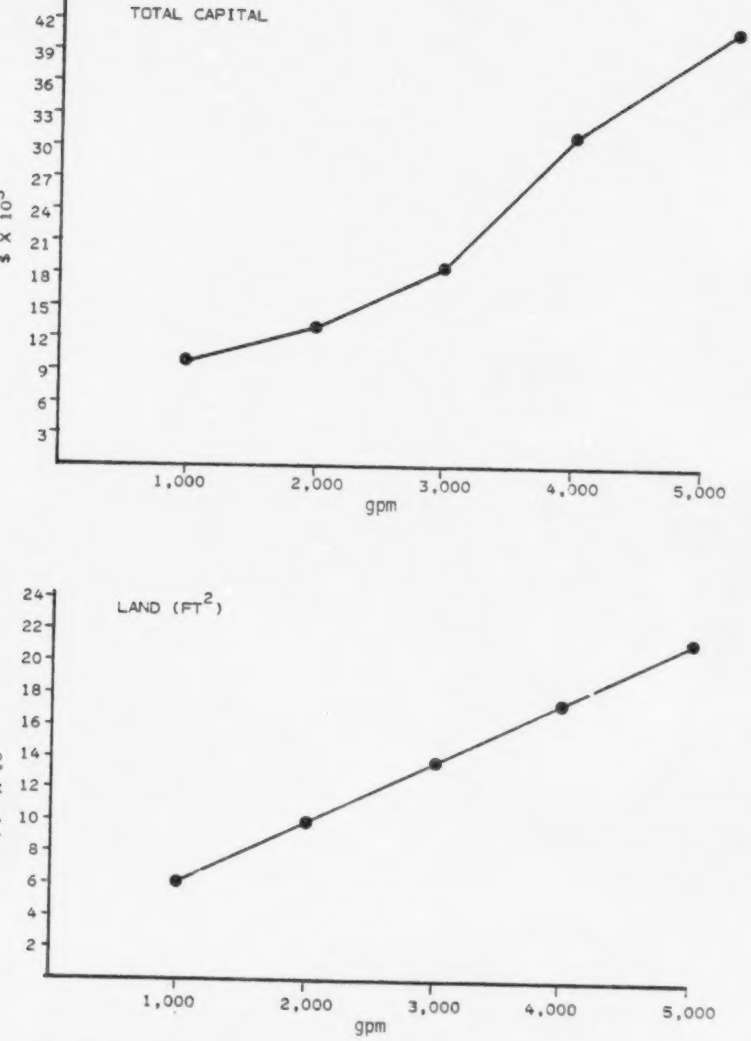
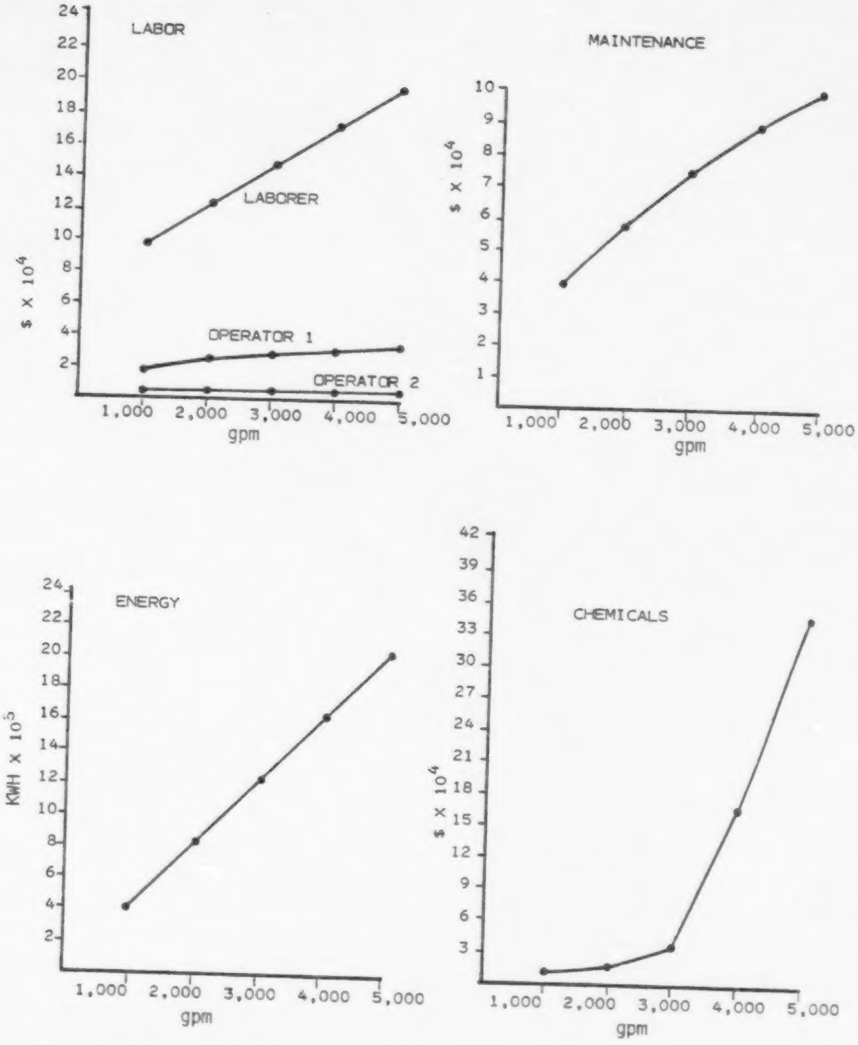


Figure 54. Aerated lagoon: changes in total capital costs with scale.


LABOR

MAINTENANCE

ENERGY

CHEMICALS

Figure 55. Aerated lagoon: changes in O&M requirements with scale.

TABLE 42. COMPUTATION OF LIFE CYCLE AVERAGE COST FOR IMPLEMENTING AERATED LAGOON (LIFETIME - 15 YEARS)

Item	Direct Operating Costs*	Indirect Operating Costs†	Sum Operating Costs	Present Value Annualized Costs#	Annual Quantity of Throughput (x 1,000 Gal.)**
YEAR 1‡	$ 795,312	$ 852,725	$1,648,037	$1,648,037	624,000
YEAR 2	874,843	868,631	1,743,474	1,584,976	624,000
YEAR 3	962,328	886,128	1,848,455	1,527,649	624,000
YEAR 4	1,058,560	905,374	1,963,934	1,475,533	624,000
YEAR 5	1,164,416	926,545	2,090,962	1,428,155	624,000
YEAR 6	1,280,858	949,834	2,230,692	1,385,084	624,000
YEAR 7	1,408,944	975,451	2,384,395	1,345,929	624,000
YEAR 8	1,549,838	1,003,630	2,553,468	1,310,333	624,000
YEAR 9	1,704,822	1,034,627	2,739,448	1,277,973	624,000
YEAR 10	1,875,304	1,068,723	2,944,027	1,248,555	624,000
YEAR 11	2,062,835	1,106,229	3,169,064	1,221,811	624,000
YEAR 12	2,269,118	1,147,486	3,416,604	1,197,499	624,000
YEAR 13	2,496,030	1,192,868	3,688,898	1,175,397	624,000
YEAR 14	2,745,633	1,242,789	3,988,421	1,155,304	624,000
YEAR 15	3,020,196	1,297,701	4,317,897	1,137,037	624,000
TOTALS			40,727,776	20,119,272	9,360,000
Simple Average (Per 1,000 Gal.)			$4.35		
Simple Average (Per Cubic Meter)			$1.15		
Life Cycle Average (Per 1,000 Gal.)				$2.15	
Life Cycle Average (Per Cubic Meter)				$0.57	

* Assumes 10% annual inflation.

† Inflation increases the administrative overhead only.

# Assumes a 10% interest/discount rate to the beginning of the first year of operation.

** 5,000 GPM x 60 min x 8 hrs/day x 260 days/yr.

‡ First year costs in mid-1978 dollars - for Chicago example.

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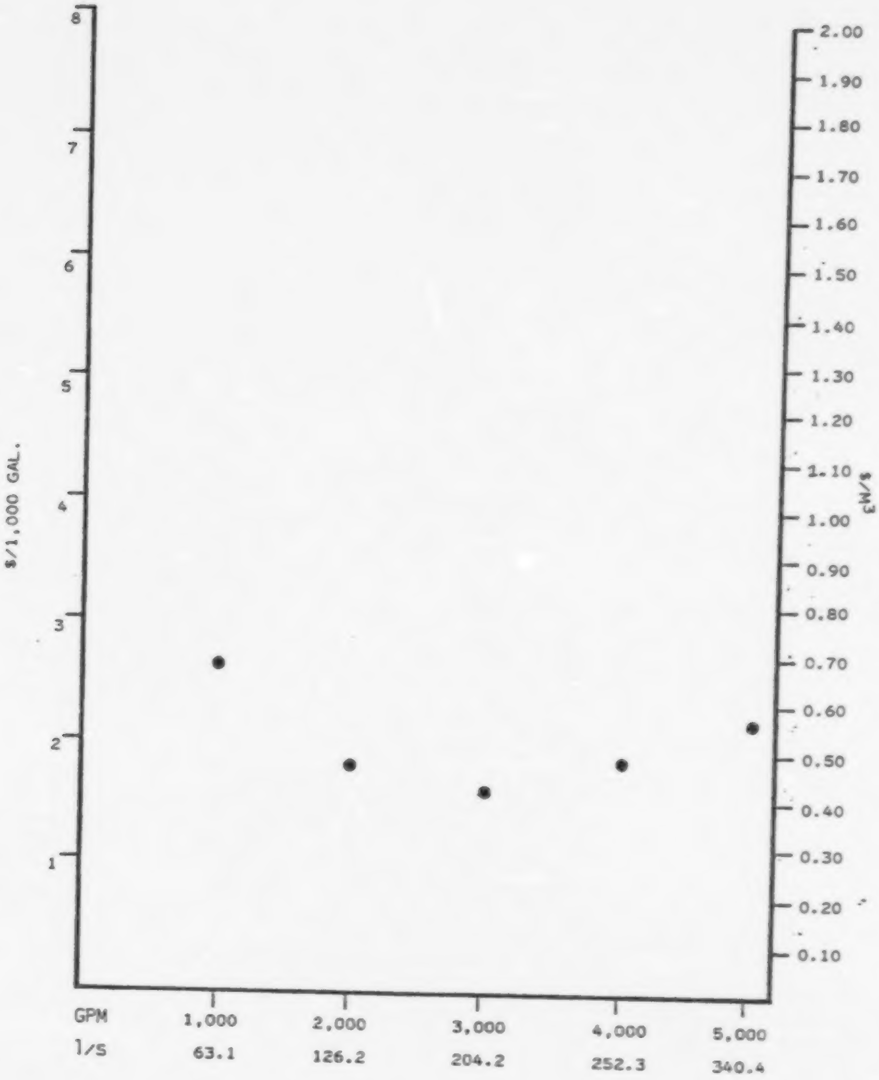

Figure 56. Aerated lagoon: life cycle costs at five scales of operation.

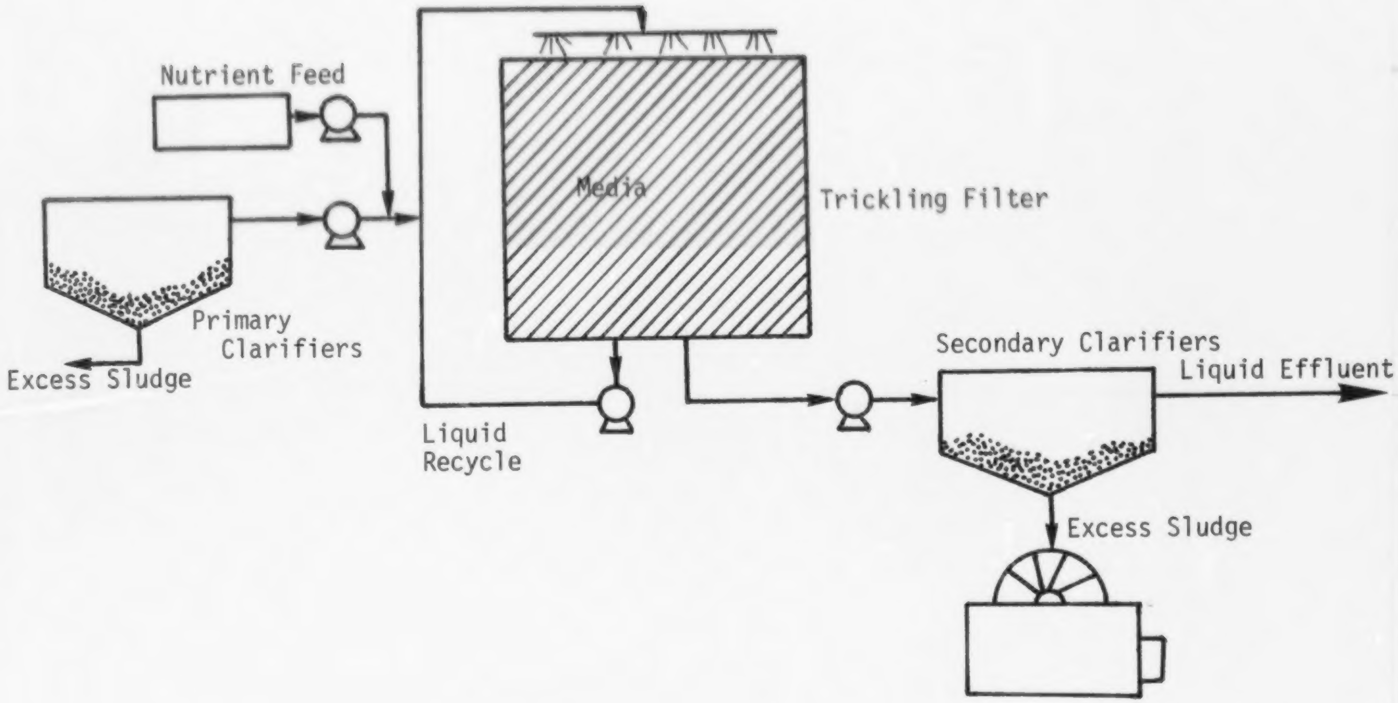
Nutrient Feed
Media
Trickling Filter
Primary Clarifiers
Excess Sludge
Liquid Recycle
Secondary Clarifiers
Liquid Effluent
Excess Sludge

Figure 57. High rate trickling filter flow diagram.

for biological growth and voids for passage of liquid and air. As primary-treated waste flows over the microbial film, the soluble organics are rapidly metabolized and the colloidal organics adsorbed onto the media surface. The bilogical slime layer consists of bacteria, protozoa and fungi. The lower portion of a deep filter frequently supports populations of nitrifying bacteria (18,19).

A cutaway view of modern trickling filter is shown in Figure 58 . The rotary distributor provides a uniform hydraulic load on the filter surface. The underdrain system carries away the effluent and excess biological solids which are removed in the secondary clarifiers. Sludge from the primary and secondary settling operations are dewatered for further management/disposal. Some of the secondary biological solids are returned to the head of the plant and mixed with the raw waste water and settled in the primary clarifiers.

Changes in Configuration with Scale

Each filter is 10 ft deep with a maximum diameter of 100 ft. The cost equations in Appendix F show how the filter and clarifiers are sized according to the influent flow rate and solids loading.

Applications

The primary objective of the trickling filter is the conversion of biodegradable organic compounds into cell mass. All organic constituents in the organic chemicals manufacturing industry waste streams, which are not biocidal and are biodegradable, can be treated (Appendix E).

Costs

The capital and O&M unit cost files (Appendices B and C) are used together with the cost equations in Appendix F to derive capital and first year operating costs for trickling filter (Tables 43 and 44). All costs are adjusted for inflation to mid-1978 values and are based on charges as they exist in the City of Chicago, Illinois.

The breakdown of capital costs for trickling filter shows that the filter, sedimentation basin, sludge dewatering and chemical feed processes all contribute substantially to the overall cost of structures and mechanical equipment. The major O&M costs are for labor ($222,944) and chemicals ($352,360) for the 5,000 gpm facility. The total capital and first year operation costs are $7,191,540 and 1,959,492, respectively.

The change in total capital costs (exclusive of land costs) according to the scale of operation is shown in Figure 59.

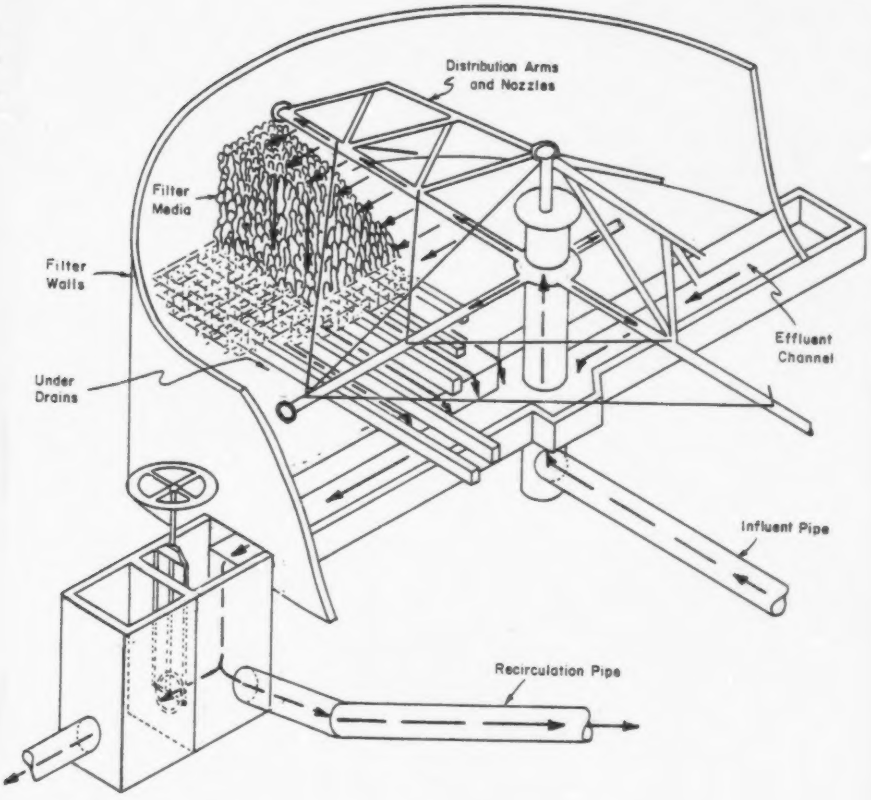
Distribution Arms and Nozzles
Filter Media
Filter Walls
Under Drains
Effluent Channel
Influent Pipe
Recirculation Pipe

Figure 58. View of trickling filter showing internal components.

TABLE 43. SUMMARY OF CAPITAL COSTS FOR TRICKLING FILTER*

Capital Cost Category Module	Costs†						Quantities	
	Site Preparation	Structures	Mechanical Equipment	Electrical Equipment	Land	Total	Land (ft^2)	Other Volume (gal)
Trickling filter	$ 69,400	$723,000	$ 85,020	$ ---	$ 93,300	----	---	2,300,000
Sedimentation basin	29,700	241,000	766,000	2,020	25,500	----	34,300	----
Clarifier	995	115,000	22,300	172	645	----	867	----
Sludge dewatering	143	34,100	735,000	7,350	3,290	----	4,430	----
Chemical feed	14,710	213,000	935,000	---	6,220	----	8,362	----
Chemical feed	8,330	107,000	29,500	---	1,520	----	2,039	----
Chemical pump	---	---	1,530	---	-----	----	---	----
Chemical pump	---	---	1,470	---	-----	----	---	----
Sludge pump	---	---	4,490	---	-----	----	---	----
Yard piping	1,125	---	72,500	---	-----	----	---	----
Total	124,403	1,433,100	2,652,810	9,542	130,475	----	49,998	2,300,000
Supplemental capital costs	---	141,303#	---	---	-----	----	---	----
Subtotal of capital costs	---	---	---	---	-----	$ 6,791,633	---	----
Working capital**	---	---	---	---	-----	60,325	---	----
AFDC‡	---	---	---	---	-----	339,582	---	----
Grand total of capital costs	---	---	---	---	-----	7,191,540	---	----

* Scale = 5,000 gpm; TSS = 500 ppm; percent solids (wt/wt) = 20.

† Mid-1978 dollars.

Building.

** At one month of direct operating costs.

‡ Allowance for funds during construction at 5% of capital costs.

TABLE 44. SUMMARY OF FIRST YEAR O&M COSTS FOR TRICKLING FILTER*

	Costs†							
	Labor							
O&M Cost Category Module	Type 1 Operator 1 ($7.77/hr)	Type 2 Operator 2 ($9.19/hr)	Type 3 Laborer ($6.76/hr)	Energy Electrical ($0.035/KWH)	Maintenance Costs	Chemical Costs	Total	Other KWH (yr)
Trickling filter	$ 1,172	$ 208	$ 19,384	$ ---	$ 9,029	$ ---	---	---
Sedimentation basin	3,911	276	40,850	102	68,600	---	---	2,914
Clarifier	10,636	755	111,078	3,102	2,230	---	---	2,914
Sludge dewatering	2,933	900	30,637	56,400	7,390	1,610	---	1,611,428
Chemical feed	---	---	---	---	900	349,000	---	---
Chemical feed	---	---	---	---	800	1,750	---	---
Chemical pump	---	---	---	35	---	---	---	1,000
Chemical pump	---	---	---	17	---	---	---	486
Sludge pump	---	---	---	863	---	---	---	24,657
Yard piping	---	---	204	---	363	---	---	---
Total	18,652	2,139	202,153	60,519	89,312	352,360	---	1,643,399
Supplemental O&M costs	---	---	---	---	1,770	---	---	---
Subtotal of direct O&M costss	---	---	---	---	---	---	$ 725,136	---
Administrative overhead#	---	---	---	---	---	---	145,027	---
Debt service and amortization **	---	---	---	---	---	---	945,499	---
Real estate taxes and insurance ‡	---	---	---	---	---	---	143,831	---
Total first year operating costs	---	---	---	---	---	---	1,959,492	---

* Scale 5,000 gpm.
† Mid-1978 dollars.
# At 20% of direct operating costs.
** At 10% interest over 15 years.
‡ At 2% of total capital.

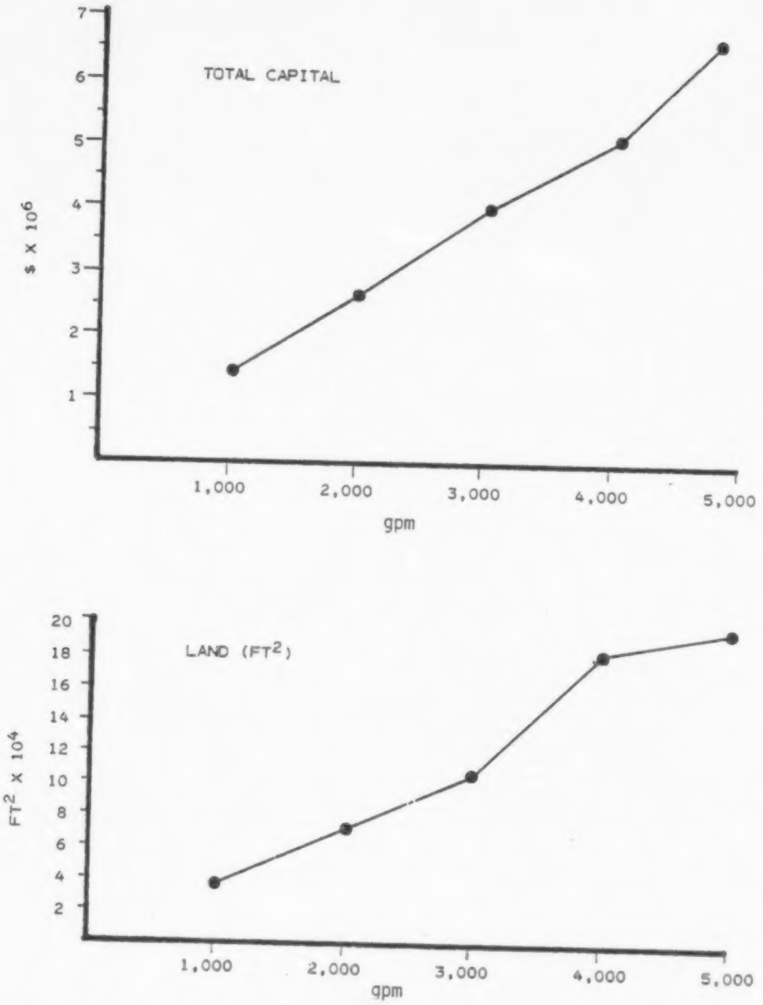

Figure 59. Trickling filter: changes in total capital costs with scale.

The capital cost at 1,000 gpm is equal to \$11.76/1,000 gal treated. This decreases to \$10.27 at 2,000 gpm and fluctuates between that value and \$10.68 as the facility increases in capacity.

Trickling filter O&M requirements are shown in Figure 60. Labor and maintenance costs demonstrate significant economies of scale; while power requirements are constant throughout the range.

The direct and indirect operating costs (including debt service and amortization) are used to calculate the average cost over the 15 year life cycle of the 5,000 gpm trickling filter facility. The life cycle average cost is \$2.37/1,000 gal (\$0.63/m^3). Figure 61 shows the life cycle average costs at five different scales of operation.

WASTE STABILIZATION POND

Description

Waste stabilization ponds are earth-diked ponds with steep sidewalls. Raw wastewater enters near the bottom at one end of the lagoon and mixes with the active microbial mass of suspended solids in the sludge blanket, which is about 6 ft deep. A discharge pipe is located on the opposite end of the lagoon submerged below the liquid surface. Excess undigested grease floats on the liquid surface of the lagoon forming a natural cover for the retention of heat and strict anaerobic conditions. In an anaerobic lagoon system, the wastewater is neither equalized nor heated. Excess sludge is washed out in the wastewater effluent and removed in a sedimentation basin. Recirculation is not necessary. Major advantages of anaerobic lagoons are: low first year operating costs, ability to accept shock and intermittent loading and simplicity of operation. Anaerobic lagoons operating at loadings of 15 to 20 lb BOD/1,000 ft^3 per day, at a detention time of 4 or more days, and at a temperature above 75°F, remove 75 to 85 percent of the influent BOD (20, 21).

Changes in Configuration with Scale

The model used to cost the example facility assumes a maximum surface area for a single pond is 15 acres. Equal sized multiple ponds are used for larger areas. Maximum waste depth is 10 ft.

Applications

As with other biological treatment processes for hazardous organic wastes, waste stabilization ponds are applied to biodegradable organic compounds in the organic chemical industry's more dilute waste streams (Appendix E).

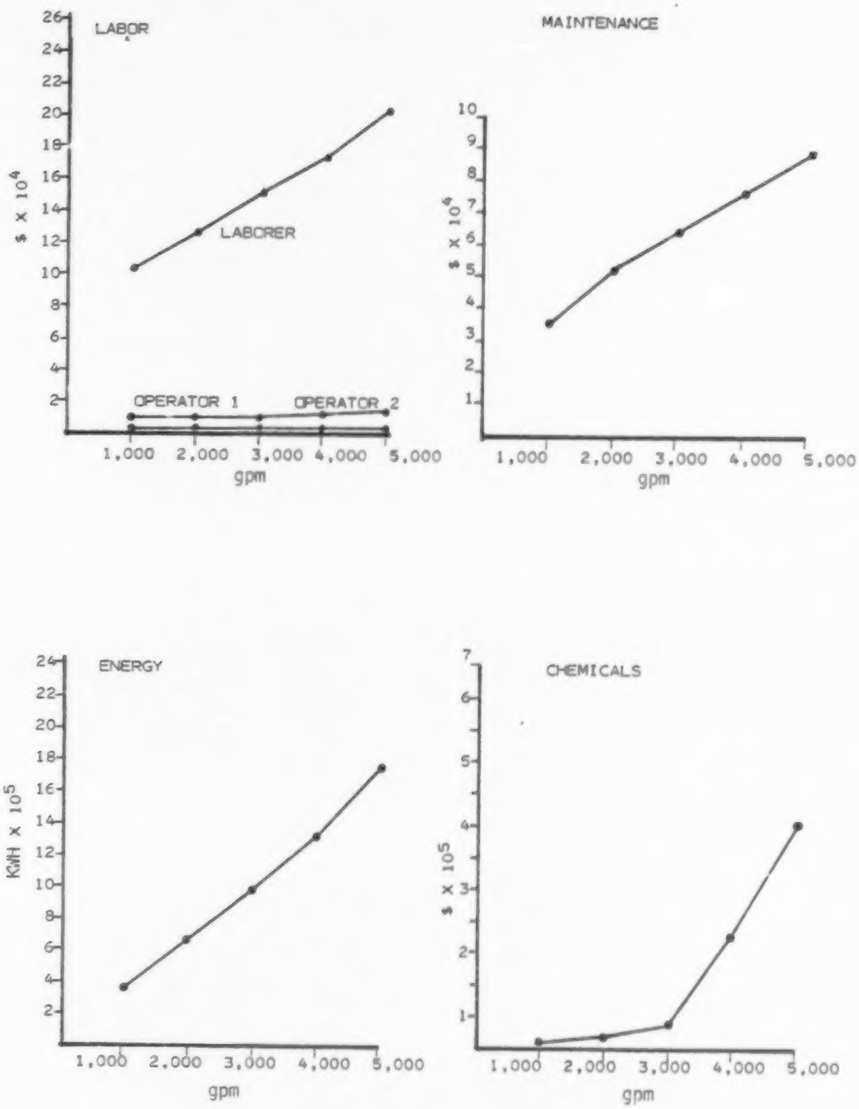

Figure 60. Trickling filter: changes in O&M requirements with scale.

TYPING GUIDE SHEET

TABLE 45. COMPUTATION OF LIFE CYCLE AVERAGE COST FOR IMPLEMENTING TRICKLING FILTER (LIFETIME - 15 YEARS)

Item	Direct Operating Costs*	Indirect Operating Costs†	Sum Operating Costs	Present Value Annualized Costs#	Annual Quantity of Throughput (x 1,000 Gal.)**
YEAR 1‡	$ 725,135	$1,234,357	$1,959,492	$1,959,492	624,000
YEAR 2	797,648	1,248,860	2,046,508	1,860,480	624,000
YEAR 3	877,413	1,264,813	2,142,226	1,770,336	624,000
YEAR 4	965,155	1,282,361	2,247,516	1,688,559	624,000
YEAR 5	1,061,670	1,301,664	2,363,334	1,614,157	624,000
YEAR 6	1,167,837	1,322,897	2,490,734	1,546,497	624,000
YEAR 7	1,284,621	1,346,254	2,630,875	1,485,129	624,000
YEAR 8	1,413,083	1,371,947	2,785,030	1,429,277	624,000
YEAR 9	1,554,391	1,400,208	2,954,599	1,378,320	624,000
YEAR 10	1,709,830	1,431,296	3,141,126	1,332,152	624,000
YEAR 11	1,880,813	1,465,493	3,346,306	1,290,001	624,000
YEAR 12	2,068,895	1,503,109	3,572,004	1,251,987	624,000
YEAR 13	2,275,784	1,544,487	3,820,271	1,217,138	624,000
YEAR 14	2,503,363	1,590,003	4,093,366	1,185,848	624,000
YEAR 15	2,753,699	1,640,070	4,393,769	1,156,879	624,000
TOTALS			43,987,156	22,166,252	9,360,000
Simple Average (Per 1,000 Gal.)			$4.70		
Simple Average (Per Cubic Meter)			$1.24		
Life Cycle Average (Per 1,000 Gal.)				$2.37	
Life Cycle Average (Per Cubic Meter)				$0.63	

---

* Assumes 10% annual inflation.

† Inflation increases the administrative overhead only.

# Assumes a 10% interest/discount rate to the beginning of the first year of operation.

** 5,000 GPM x 60 min x 8 hrs/day x 260 days/yr.

‡ First year costs in mid-1978 dollars - for Chicago example.

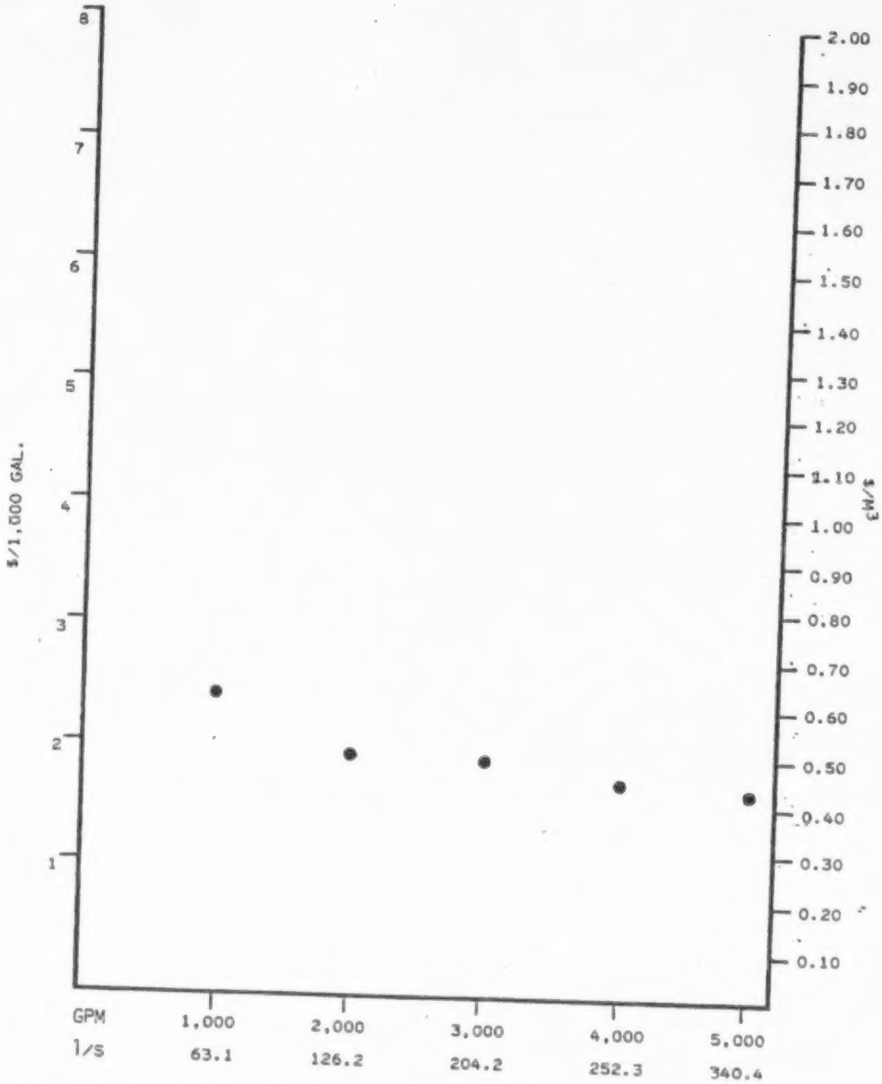

Figure 61. Trickling filter: life cycle costs at five scales of operation.

Costs

Summaries of capital and first year operating costs for waste stabilization pond are shown in Tables 46 and 47. These estimates are based on mid-1978 costs for components, unit processes, labor, utilities, etc., as applicable in Chicago, Illinois. The estimates are based on the cost files in Appendices B and C, and the cost equations included in Appendix F.

As shown in Table 46 , the two most costly unit processes are the waste stabilization pond and the sedimentation basin. Most of the costs for the pond are included in site preparation (excavation). Sludge dewatering costs are not included in this assessment. The operating costs are those for labor.

Figure 62 shows the capital costs (exclusive of land costs) for five scales of operation and the corresponding land area requirements. The capital costs demonstrate significant economies of scale throughout the range. The costs at 1,000 and 5,000 gpm are \$7.50 and \$5.91/1,000 gal of waste treated. These savings are attributable to the use of common sidewalls, pumps, distribution piping and solids removal processes for multiple pond systems.

The O&M requirements for waste stabilization pond, as a function of scale are shown in Figure 63. Labor and maintenance show economies of scale, while power requirements (for wast pumping) fluctuates between 0.18 and 0.40 kwh/1,000 gal of waste treated. There are no chemical requirements associated with the example technology.

The average cost of the 5,000 gpm facility, over a five-year life cycle, is \$2.95/1,000 gal (\$0.76/m^3) (Table 48). The life cycle average cost at five scales of operation is shown in Figure 64. The data reflect the significant economy of scale for the capital expenditure.

ANAEROBIC DIGESTION

Description

Anaerobic digestion of sludges is a treatment process used for further degradation of organic materials and solids volume reduction. Typically, raw sludge from a biological treatment process (e.g. activated sludge, aerated lagoon, trickling filter, etc.) is retained and circulated in a digester. The solids are degraded by the anaerobic biological culture maintained in the digester environment.

Figure 65 is a typical flow and installation diagram for a single highrate digester system.

TABLE 46. SUMMARY OF CAPITAL COSTS FOR WASTE STABILIZATION POND*

	Costs†							Quantities	
Capital Cost Category Module	Site Preparation	Structures	Mechanical Equipment	Electrical Equipment	Land	Other	Total	Land (ft^2)	Other
Waste stabilization pond	$ 539,000	$ 1,734	$ 720	---	$ 3.22×10^6	1.9×10^6	---	4.33×10^6	117,709
Waste pump	---	---	10,800	---	---	---	---	---	---
Yard piping	900	---	55,200	---	---	---	---	---	---
Sedimentation basin	29,700	241,000	766,000	2,020	25,500	---	---	34,300	---
Total	569,600	242,734	832,720	2,020	3.25×10^6	1.9×10^6	---	4.36×10^6	117,709
Supplemental capital costs	---	141,303#	---	---	---	---	---	---	---
Subtotal of capital costs	---	---	---	---	---	---	$6,938,377	---	---
Working capital**	---	---	---	---	---	---	7,766	---	---
AFDC †	---	---	---	---	---	---	346,919	---	---
Grand total of capital costs	---	---	---	---	---	---	7,293,062	---	---

* Scale = 5,000 gpm.

† Mid-1978 dollars.

Building.

** At one month of direct operating costs.

‡ Allowance for funds during construction at 5% of capital costs.

TABLE 47. SUMMARY OF FIRST YEAR O&M COSTS FOR WASTE STABILIZATION POND*

	Costs †						
	Labor						
O&M Cost Category Module	Type 1 Operator 1 ($7.77/hr)	Type 2 Operator 2 ($9.19/hr)	Type 3 Laborer ($6.76/hr)	Energy Electrical ($0.035/KWH)	Maintenance Costs	Total	Other KWH (yr)
Waste stabilization pond	$7,333	$ 4,501	$ 17,460	$ ---	$ 245	---	---
Waste pump	---	---	---	8,630	---	---	246,571
Yard piping	---	---	179	---	276	---	---
Sedimentation basin	3,911	277	40,850	102	7,660	---	2,914
Total	11,244	4,778	58,489	8,732	8,181	---	249,485
Supplemental O&M costs	---	---	---	---	1,770	---	---
Subtotal of direct O&M costs	---	---	---	---	---	$ 93,194	---
Administrative overhead#	---	---	---	---	---	18,639	---
Debt service and amortization**	---	---	---	---	---	1,923,910	---
Real estate taxes and insurance ‡	---	---	---	---	---	145,861	---
Total first year operating costs	---	---	---	---	---	2,181,604	---

*Scale = 5,000 gpm.
† Mid-1978 dollars.
# At 20% of direct operating costs.
** At 10% interest over 5 years.
‡ At 2% of total capital.

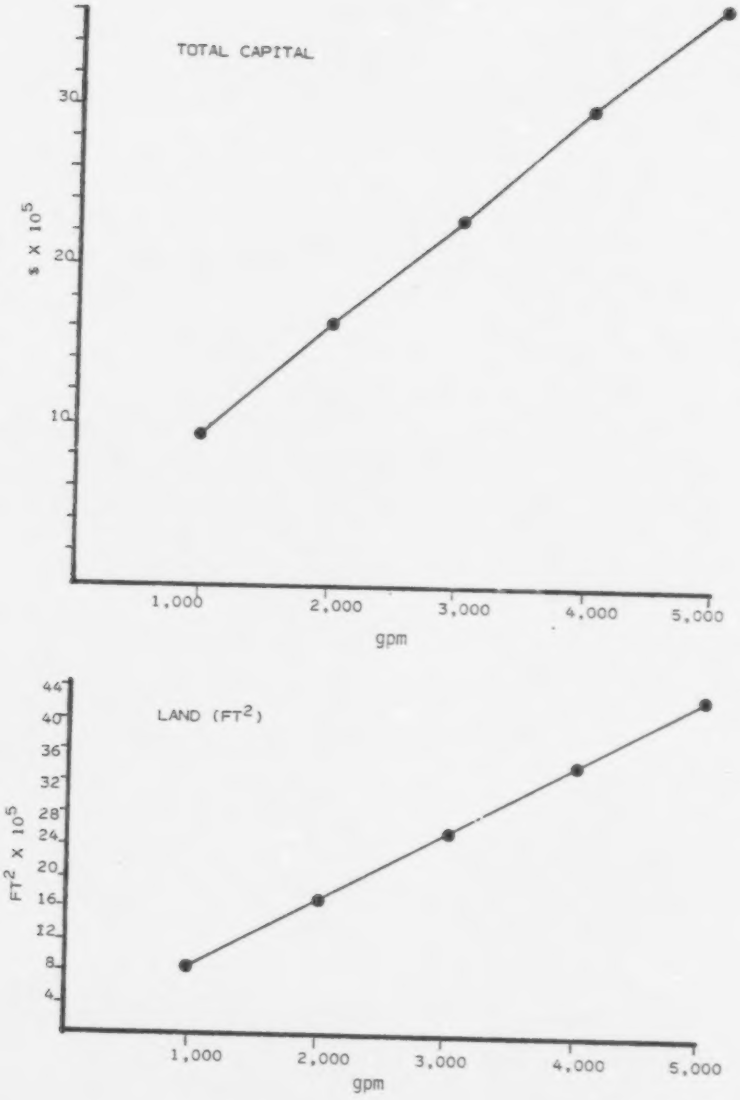

Figure 62. Waste stabilization pond: changes in total capital costs with scale.

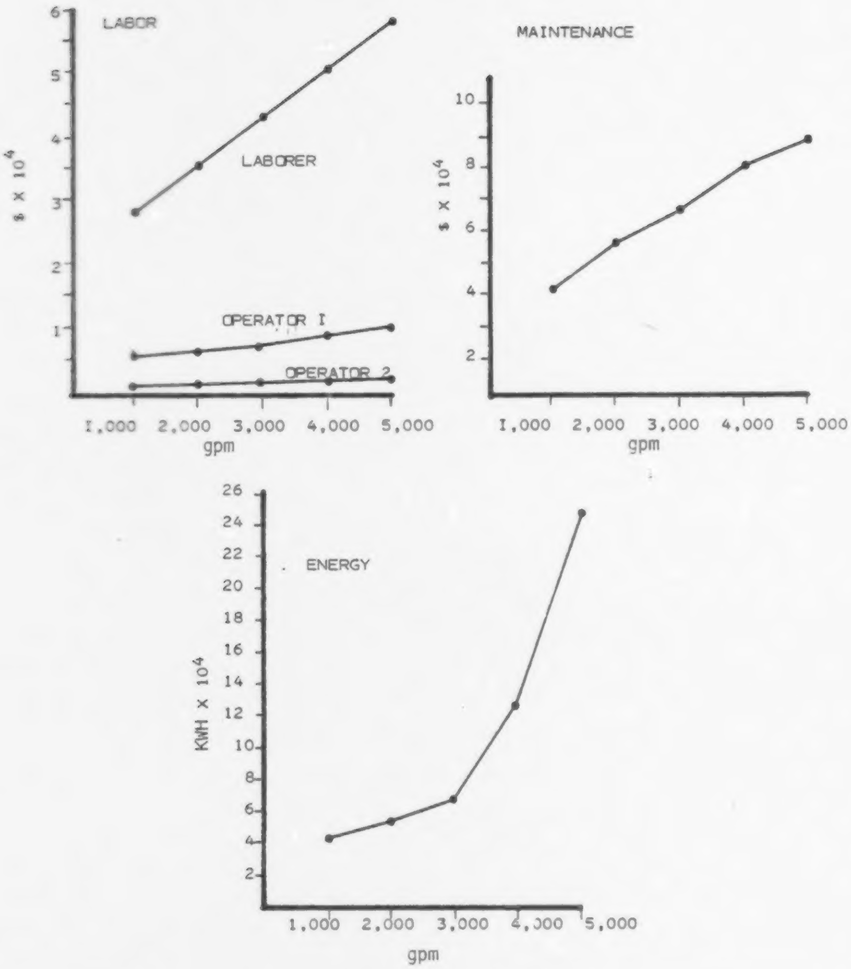

Figure 63. Waste stabilization pond: changes in O&M requirements with scale.

TABLE 48. COMPUTATION OF LIFE CYCLE AVERAGE COST FOR IMPLEMENTING WASTE STABILIZATION POND (LIFETIME - 5 YEARS)

Item	Direct Operating Costs*	Indirect Operating Costs†	Sum Operating Costs	Present Value Annualized Costs#	Annual Quantity of Throughput (x 1,000 Gal.)**
YEAR 1‡	$ 93,194	$2,088,410	$2,181,604	$2,181,604	624,000
YEAR 2	102,513	2,090,274	2,192,787	1,993,243	624,000
YEAR 3	112,765	2,092,324	2,205,089	1,821,845	624,000
YEAR 4	124,041	2,094,580	2,218,621	1,666,850	624,000
YEAR 5	136,445	2,097,058	2,233,503	1,525,483	624,000
TOTALS			11,031,604	9,189,025	3,120,000
Simple Average (Per 1,000 Gal.)			$3.54		
Simple Average (Per Cubic Meter)			$0.94		
Life Cycle Average (Per 1,000 Gal.)				$2.94	
Life Cycle Average (Per Cubic Meter)				$0.78	

* Assumes 10% annual inflation.

† Inflation increases the administrative overhead only.

# Assumes a 10% interest/discount rate to the beginning of the first year of operation.

** 5,000 GPM x 60 min x 8 hrs/day x 260 days/yr.

‡ First year costs in mid-1978 dollars - for Chicago example.

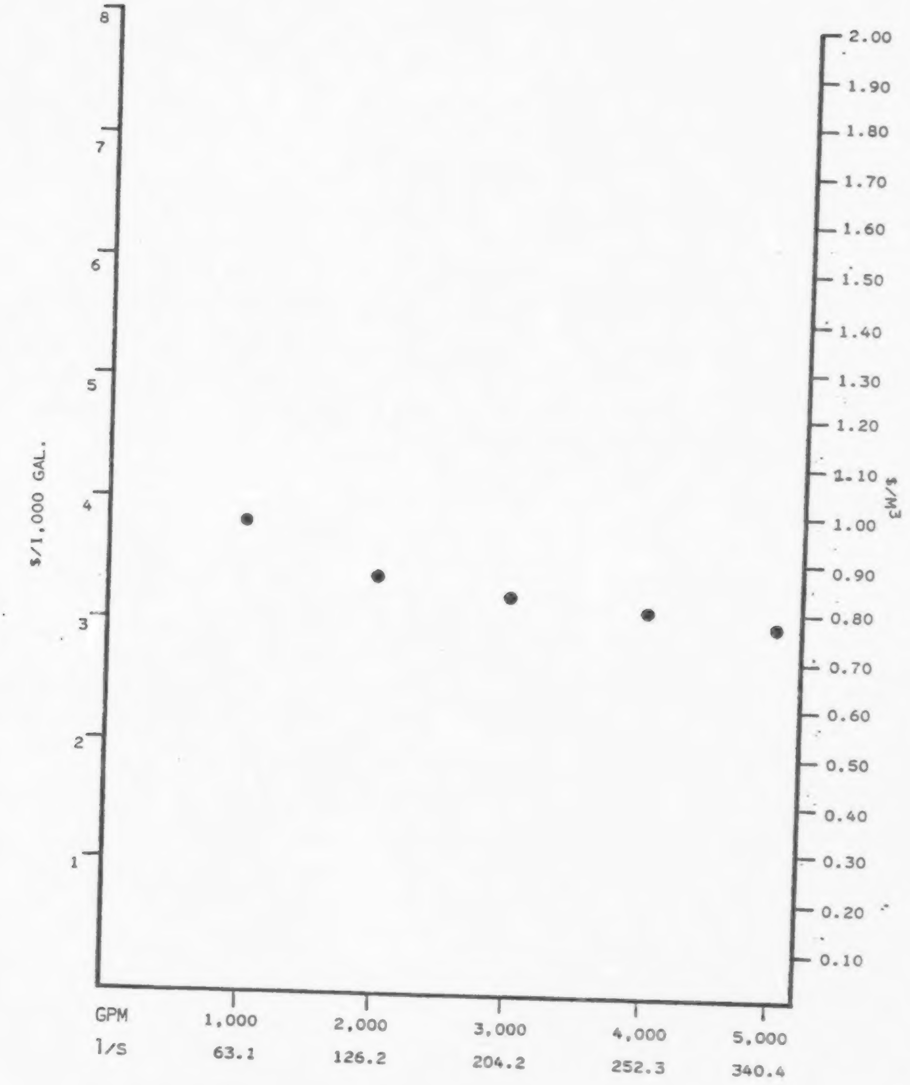

Figure 64. Waste stabilization pond: life cycle costs at five scales of operation.

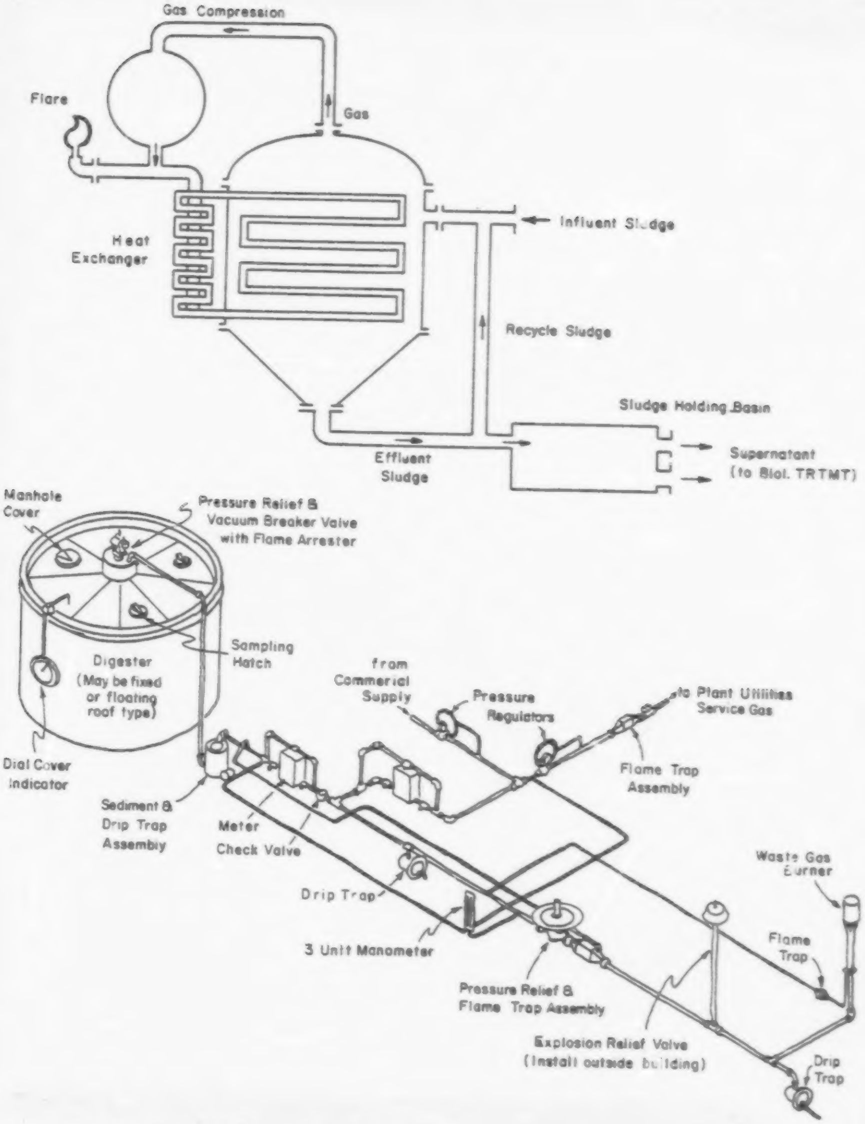
Gas Compression
Flare
Gas
Heat Exchanger
Influent Sludge
Recycle Sludge
Sludge Holding Basin
Effluent Sludge
Supernatant (to Biol. TRTMT)
Manhole Cover
Pressure Relief & Vacuum Breaker Valve with Flame Arrester
Sampling Hatch
Digester (May be fixed or floating roof type)
Dial Cover Indicator
from Commerical Supply
Pressure Regulators
to Plant Utilities Service Gas
Flame Trap Assembly
Sediment & Drip Trap Assembly
Meter
Check Valve
Drip Trap
3 Unit Manometer
Waste Gas Burner
Flame Trap
Pressure Relief & Flame Trap Assembly
Explosion Relief Valve (Install outside building)
Drip Trap

Figure 65. Typical flow and installation diagram: single digestor system.

Sludge is pumped to the digester continuously or by time clock on a 30 min to 2 hr cycle from the equalization basin. The incoming sludge displaces digested sludge to a holding tank. Because there is no supernatant separation in the high-rate digester, and because the total solids are reduced by 45 to 50 percent and given off as gas, the digested sludge is about half as concentrated as the raw sludge feed (22).

Changes in Configuration with Scale

Additional equalization and digestion tanks are provided as necessary to provide the required retention time. The cost equations in Appendix F shows how the digester capacity is matched to the sludge loading rate.

Applications

Anaerobic digestion is applied to all biological sludges from aerated lagoon systems, trickling filters, and activated sludge treatment processes. It is used to reduce sludge dewatering and land disposal requirements and is not a biological treatment alternative for most raw aqueous waste streams.

Costs

Capital and first year operating costs are calculated for anaerobic digestion (Tables 49and 50). The most costly unit processes are the sludge equalization digester vessels and dewatering facilities for the digested sludge. The total capital costs for the Chicago-based example are $2,896,454. Major operating costs include labor and energy for sludge circulation. The total first year operating costs are $814,025.

Figure 66 shows the capital costs (excluding land costs) at five scales of operation for the technology. The accompanying graph shows the land area requirements at the same scales of operation. The capital cost data indicates some economy of scale throughout the range studied (costs decrease from $20.36/1,000 gal at 1,000 gpm to $18.84/1,000 gal at 5,000 gpm).

Figure 67 shows the fluctuation in O&M requirements with scale for the model facility (operating 8 hr/day and 260 day/yr). Labor and maintenance costs demonstrate economies of scale (labor costs decrease from $0.70 to $0.28/1,000 gal over the range studied). Power requirements (22.29 kwh/1,000 gal) and chemical requirements ($0.02/1,000 gal) remain fairly constant at the five scales of operation.

The average cost of the Chicago-based model facility, over a life cycle of 10 years, is calculated in Table 51. The life cycle average cost is $5.13/1,000 gal ($1.36/m^3) for the 1,000 gpm facility. Figure 68 shows the variation in the average

TABLE 49. SUMMARY OF CAPITAL COSTS FOR ANAEROBIC DIGESTION*

Capital Cost Category Module	Costs†						Quantities	
	Site Preparation	Structures	Mechanical Equipment	Electrical Equipment	Land	Total	Land (ft^2)	Other No. of Units
Sludge equalization	$ 144	$ 11,650	$ 266,000	$ ---	$ 1,360	---	1,824	19
Sludge digestor	139,757	1,335,640	171,000	8,550	195,000	---	262,632	19
Chemical feed	390	2,130	2,030	---	321	---	432	--
Dewatering	107	25,600	551,000	5,510	2,470	---	3,320	--
Chemical pump	---	---	1,470	---	---	---	---	--
Sludge pump	---	---	9,110	---	---	---	---	--
Sludge pump	---	---	9,110	---	---	---	---	--
Yard piping	225	---	1,130	---	---	---	---	--
Total	140,623	1,375,020	1,010,850	14,060	199,151	---	268,208	38
Supplemental capital costs	---	---	---	---	---	---	---	--
Subtotal of capital costs	---	---	---	---	---	$ 2,739,704	---	--
Working capital**	---	---	---	---	---	19,765	---	--
AFDC‡	---	---	---	---	---	136,985	---	--
Grand total of capital costs	---	---	---	---	---	2,896,454	---	--

* Scale = 1,000 gpm.

† Mid-1978 dollars.

** At one month of direct operating costs.

‡ Allowance for funds during construction at 5% of capital costs.

TABLE 50. SUMMARY OF FIRST YEAR O&M COSTS FOR ANAEROBIC DIGESTION*

	Costs†							
	Labor							
O&M Cost Category Module	Type 1 Operator 1 ($7.77/hr)	Type 2 Operator 2 ($9.19/hr)	Type 3 Laborer ($6.76/hr)	Energy Electrical ($0.035/KWH)	Maintenance Costs	Chemical Costs	Total	Other KWH (yr)
Sludge equalization	$ 4,909	$ 326	$ 30,861	$ 51,600	$ 27,416	$ ---	---	1,473,700
Sludge digestor	3,742	1,162	23,061	---	17,916	---	---	---
Chemical feed	---	---	---	---	300	175	---	---
Sludge dewatering	1,963	683	20,509	42,300	5,540	1,210	---	1,208,571
Chemical pump	---	---	---	17	---	---	---	486
Sludge pump	---	---	---	1,730	---	---	---	49,429
Sludge pump	---	---	---	1,730	---	---	---	49,429
Yard piping	---	---	103	---	6	---	---	---
Total	10,614	2,171	74,534	97,377	51,178	1,385	---	2,781,615
Supplemental O&M Cost	---	---	---	---	---	---	---	---
Subtotal of direct O&M cost	---	---	---	---	---	---	$ 237,259	---
Administrative overhead#	---	---	---	---	---	---	47,452	---
Debt service and amortization**	---	---	---	---	---	---	471,385	---
Real estate taxes and insurance ‡	---	---	---	---	---	---	57,929	---
Total first year operating cost	---	---	---	---	---	---	814,025	---

* Scale = 1,000 gpm.

† Mid-1978 dollars.

# At 20% of direct operating costs.

** At 10% interest over 10 years.

‡ At 2% of total capital.

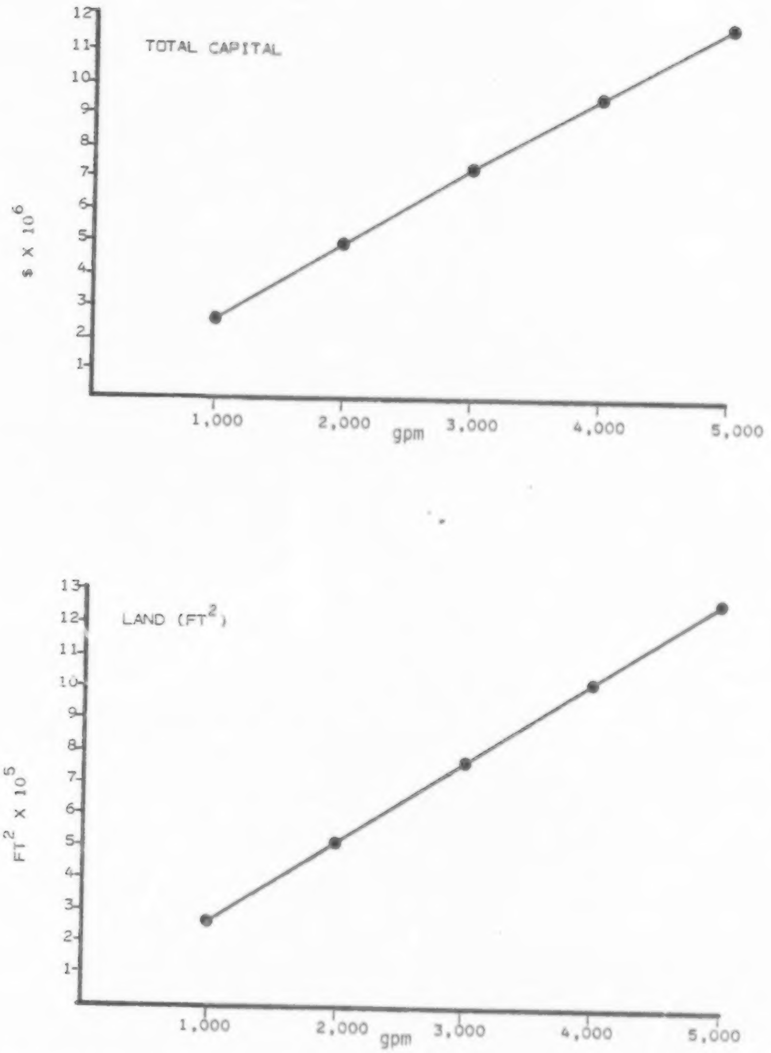

Figure 66. Anaerobic digestion: changes in total capital costs with scale.

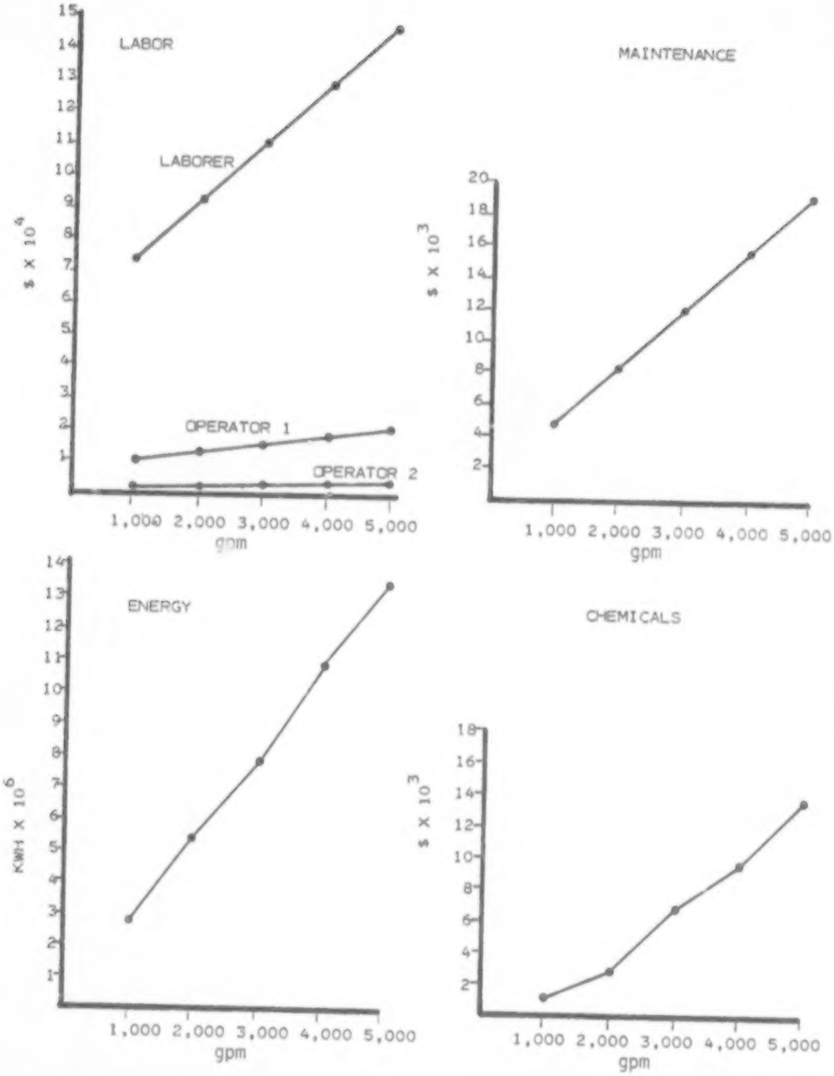

Figure 67. Anaerobic digestion: changes in O&M requirements with scale.

51

TABLE 51. COMPUTATION OF LIFE CYCLE AVERAGE COST FOR IMPLEMENTING ANAEROBIC DIGESTION (LIFETIME - 10 YEARS)

Item	Direct Operating Costs*	Indirect Operating Costs†	Sum Operating Costs	Present Value Annualized Costs#	Annual Quantity of Throughput (x 1,000 Gal.)**
YEAR 1‡	$237,259	$576,766	$ 814,025	$814,025	124,800
YEAR 2	260,985	581,511	842,496	765,913	124,800
YEAR 3	287,083	586,731	873,814	722,120	124,800
YEAR 4	315,792	592,473	908,265	682,379	124,800
YEAR 5	347,370	598,788	946,158	646,226	124,800
YEAR 6	382,108	605,736	987,844	613,352	124,800
YEAR 7	420,319	613,378	1,033,697	583,522	124,800
YEAR 8	462,351	621,785	1,084,136	556,379	124,800
YEAR 9	508,586	631,032	1,139,618	513,632	124,800
YEAR 10	559,444	641,203	1,200,647	509,194	124,800
TOTALS			9,830,700	6,406,742	1,248,000
Simple Average (Per 1,000 Gal.)			$7.88		
Simple Average (Per Cubic Meter)			$2.08		
Life Cycle Average (Per 1,000 Gal.)				$5.13	
Life Cycle Average (Per Cubic Meter)				$1.36	

---

* Assumes 10% annual inflation.

† Inflation increases the administrative overhead only.

# Assumes a 10% interest/discount rate to the beginning of the first year of operation.

** 1,000 GPM x 60 min x 8 hrs/day x 260 days/yr.

‡ First year costs in mid-1978 dollars - for Chicago example

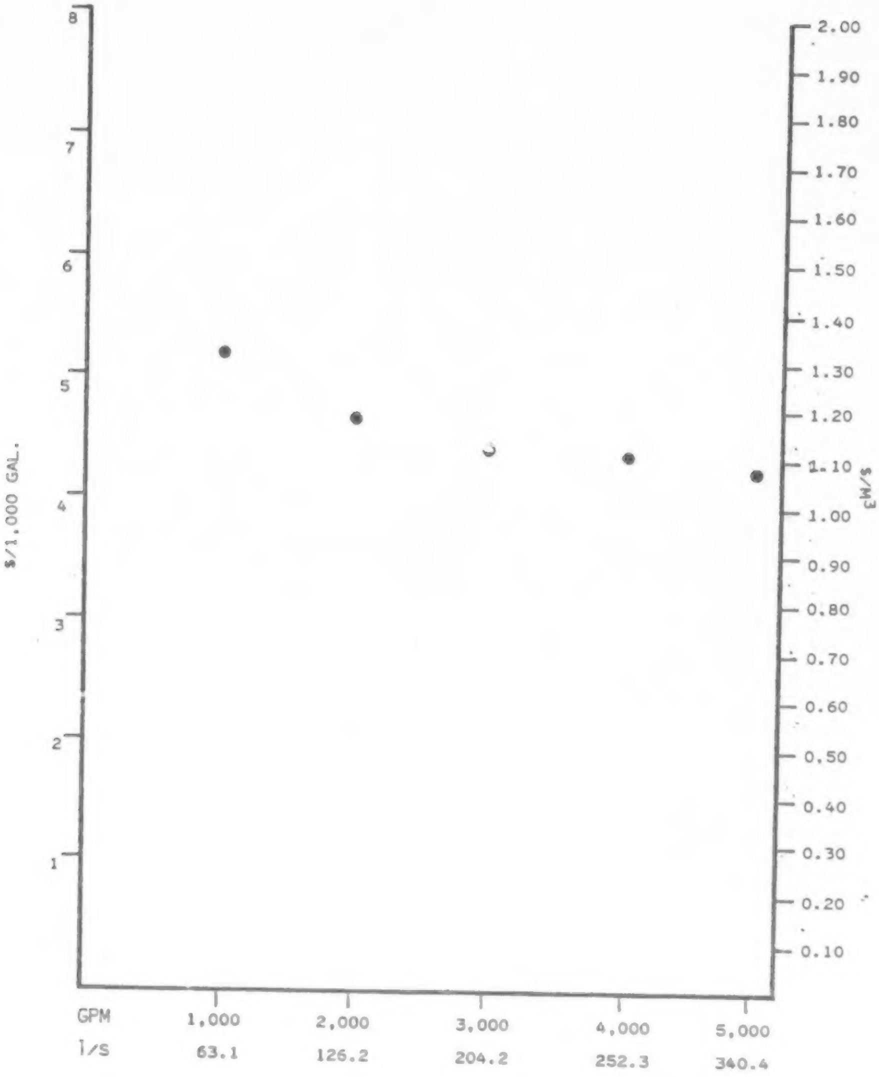

Figure 68. Anaerobic digestion: life cycle costs at five scales of operation.

cost with scale. The reduction in capital costs, labor and maintenance requirements per unit of waste treated is reflected in the life cycle calculations.

CARBON ADSORPTION

Description

Aqueous waste streams are contacted with carbon by passing it through a vessel filled with carbon granules or with a carbon slurry (Figure 69). Impuities are removed from the water by adsorption when sufficient contact time is provided for this process. The carbon system usually consists of a number of columns or basins used as contactors. These are connected to a regeneration system.

After a period of use, the carbon adsorptive capacity is exhausted. The carbon must then be taken out of service and regenerated thermally by combustion of the organic adsorbate. Fresh carbon is routinely added to the system to replace that lost during hydraulic transport and regeneration. These losses include both attrition due to physical deterioration and burning during the actual regeneration process. A multiple hearth furnace is included in the regeneration system.

Certain organic compounds in wastewaters are resistant to biological degradation and many others are toxic or nuisances (odor, taste, color forming) even at low concentrations. Low concentrations are not readily removed by conventional treatment methods. Activated carbon has an affinity for organics, and its use for organic contaminant removal from wastewaters is widespread (23).

Changes in Configuration with Scale

Depending on the hydraulic loading imposed on the contactor, high flow rates may identify the need for multiple contactors. Thus, a modest hydraulic loading, coupled with the need for long detention time, may require two or more carbon contactors in a series. A large plant throughout (i.e., 1 mgd or greater) will, for the typical range of hydraulic loading (2 to 10 gpm/ft^2), require a system in which two or more modules are arrayed in parallel.

Applications

Activated carbon presently has a wide range of applications for treating aqueous and dilute industrial wastes. It is estimated that there are 100 large-scale systems currently in use for industrial/municipal wastewater treatment (24).

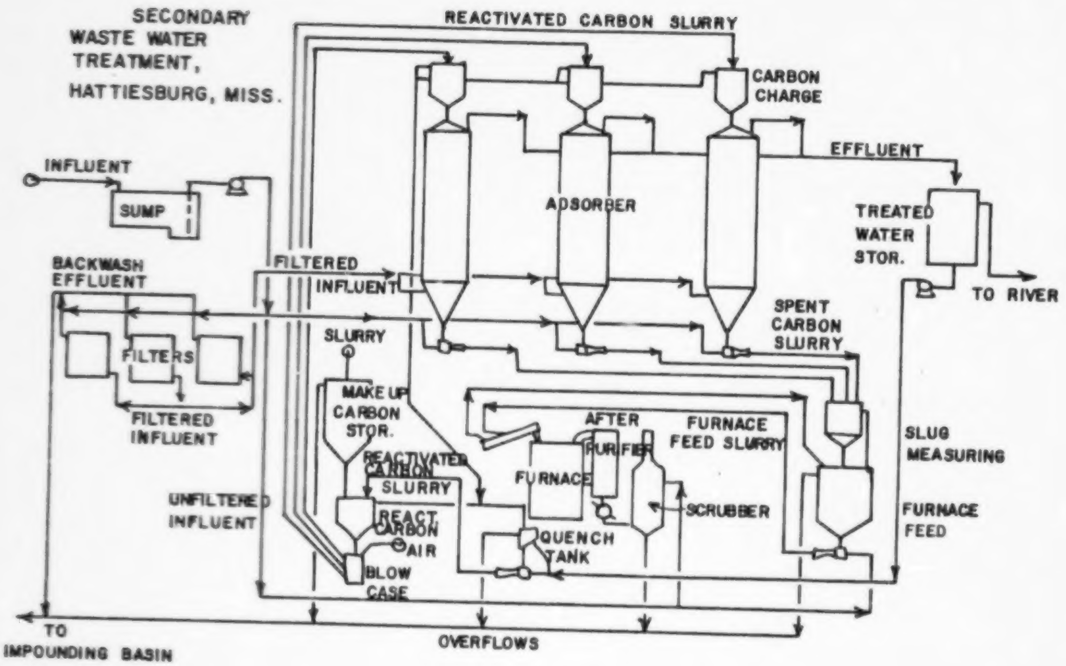
SECONDARY WASTE WATER TREATMENT, HATTIESBURG, MISS.
REACTIVATED CARBON SLURRY
CARBON CHARGE
EFFLUENT
INFLUENT
SUMP
ADSORBER
TREATED WATER STOR.
TO RIVER
BACKWASH EFFLUENT
FILTERED INFLUENT
FILTERS
FILTERED INFLUENT
SPENT CARBON SLURRY
SLURRY
MAKE UP CARBON STOR.
AFTER PURIFIER
FURNACE FEED SLURRY
SLUG MEASURING
REACTIVATED CARBON SLURRY
FURNACE
SCRUBBER
UNFILTERED INFLUENT
REACT. CARBON
AIR
QUENCH TANK
FURNACE FEED
BLOW CASE
TO IMPOUNDING BASIN
OVERFLOWS

Figure 69. Schematic diagram of a carbon adsorption system incorporating thermal regeneration of the carbon.

A wide variety of organic and inorganic solutes may be efficiently adsorbed on activated carbon. Applications involving organic solutes are more prevalent and will be most attractive when the solutes have a high molecular weight, low water solubility, low polarity and low degree of ionization.

Highly soluble organics, which often contain two or more hydrophilic groups, are difficult to remove. For example, the adsorption of glycols from an industrial waste stream was found to be unfeasible in one recent study because of the low capacity of the carbon for the glycols. In another case, the treatment of wastewaters from a polyvinyl chloride production plant was found to be impractical. Poor adsorption characteristics were attributed to the presence of long-chain organic soaps contained in the wastes. For some examples of low adsorption efficiency (e.g. acetic acid adsorption), the higher process costs may be offset by solute recovery. Macro-molecules, including certain dyes, may be too large to reach a significant fraction of the carbon's internal pores and may therefore be difficult to remove. Most industrial waste streams contain multiple impurities, some of which are easily adsorbed on carbon, while others are not. In considering the use of an activated carbon system, a series of laboratory tests is mandatory. Such tests should include both equilibrium adsorption isotherms and carbon column studies.

Carbon adsorption of inorganic compounds (e.g.,the removal of cyanide and chromium from the electroplating wastes) has been found to be practical. Other sources indicate that a wide variety of other inorganics will adsorb on activated carbon. However, adsorption may be quite variable from chemical to chemical; furthermore, it is likely to be highly pH dependent, and thermal or chemical regeneration may not be feasible. In general, strong electrolytes will not be adsorbed on carbon. Removal of inorganic solutes by carbon will generally involve invluent concentration of less than 1,000 ppm (preferably less than 500 ppm). Processes other than physical or chemical adsorption may be involved. Plating may occur in some cases (e.g., with ferric salts), and chemical reactions may take place in others (e.g., reduction of ammonia to chloramines followed by adsorption of the chloramines).

Costs

Capital costs for carbon adsorption are itemized in Table 52. The most costly unit process is the carbon adsorption columns, together with the regeneration system (included in the carbon adsorption costs). The total capital cost for a 5,000 gpm facility is $1,205,423 (mid-1978 dollars).

Table 53 summarizes the first year operating costs. Energy and chemical requirements comprise over 90 percent of the direct O&M costs. The total first year operating costs, including

TABLE 52. SUMMARY OF CAPITAL COSTS FOR CARBON ADSORPTION*

Capital Cost Category Module	Costs						Quantities	
	Site Preparation	Structures	Mechanical Equipment	Electrical Equipment	Land	Total	Land (ft^2)	Other Steam lbs/hr
Carbon adsorption	$ 11,400	$ 52,900##	$ 552,000	$ 552	$ 3,430	---	4,620	---
Steam generator	13	1,163	12,900	--	124	---	167	664
Waste pump	---	---	10,800	--	---	---	---	---
Piping	1,125	---	72,500	--	---	---	---	---
Total	12,538	54,063	648,200	552	3,554	---	4,787	664
Supplemental capital Costs	---	141,303	---	--	---	---	---	---
Subtotal of capital costs	---	---	---	--	---	$ 860,210	---	---
Working capital**	---	---	---	--	---	302,202	---	---
AFDC‡	---	---	---	--	---	43,011	---	---
Grand total of capital costs	---	---	---	--	---	1,205,423	---	---

* Scale = 5,000 gpm.

† Mid-1978 dollars.

Building.

** At one month of direct operating costs.

‡ Allowance for funds during construction at 5% of capital costs.

Includes initial carbon charge.

TABLE 53. SUMMARY OF FIRST YEAR O&M COSTS FOR CARBON ADSORPTION*

	Costs†								
	Labor								
O&M Cost Category Module	Type 1 Operator 1 ($7.77/hr)	Type 2 Operator 2 ($9.19/hr)	Type 3 Laborer ($6.76/hr)	Energy Electrical ($0.035/KWH)	Maintenance Costs	Chemical Costs	Total	Other KWH (yr)
Carbon adsorption	35,260	10,396	40,857	2,100,000	119,000	1,290,000	---	3,744,000
Steam generator	590	105	7,793	5,280	---	6,170	---	---
Waste pump	---	---	---	8,630	---	---	---	---
Piping	---	---	204	---	363	---	---	---
Total	35,850	10,501	48,854	2,113,910	119,363	1,296,170	---	3,744,000
Supplemental O&M costs	---	---	---	---	1,770	---	---	---
Subtotal of direct O&M costs	---	---	---	---	---	---	3,626,418	---
Administrative overhead#	---	---	---	---	---	---	725,284	---
Debt service and amortization**	---	---	---	---	---	---	247,606	---
Real estate taxes and insurance‡	---	---	---	---	---	---	24,108	---
Total first year operating costs	---	---	---	---	---	---	4,623,416	---

* Scale = 5,000 gpm.

† Mid-1978 dollars.

# At 20% of direct operating costs.

** At 10% interest over 7 years.

‡ At 2% of total capital.

administrative overhead ($725,284), debt service and amortization ($247,606) and real estate taxes and insurance ($24,108) is $4,623,416.

Figure 70 shows the capital costs (excluding land costs) for five scales of operation and the corresponding land requirements for carbon adsorption. The capital costs per 1,000 gallons of waste treated decrease from $1.78 at 1,000 gpm to $1.28 at 3,000 gpm. The same costs then increase slightly to $1.37 at 5,000 gpm. The costs for carbon adsorption, as well as the steam generation system, offset any economy of scale for capital at larger capacity facilities.

The O&M requirements for carbon adsorption as a function of scale are shown in Figure 71. Total labor costs are $47,800 and $95,205 at 1,000 and 5,000 gpm, respectively. A significant portion of these costs are attributable to the operation -1 and laborer labor categories. Maintenance also demonstrates economies of scale ($0.72/1,000 gal decreasing to $0.19/1,000 gal from 1,000 to 5,000 gpm). Energy requirements (mainly for carbon regeneration) and chemical requirements (make-up carbon) also exhibit economies of scale:

Scale (gpm)	1,000	2,000	3,000	4,000	5,000
Energy(kwh/1,000 gal)	14.94	8.05	5.75	4.60	6.00
Chemicals ($/1,000 gal)	10.38	5.19	3.46	2.60	2.08

The average cost of the example facility, over a life cycle of 7 years, is calculated in Table 54. The life cycle average cost for the 5,000 gpm facility is $7.31/1,000 gal ($1.93/m^3). Figure 72 shows the life cycle average cost at five scales of operation. The analysis reflects the significant economies of scale for all O&M categories.

ACTIVATED SLUDGE

Description

Activated sludge processes are used for both secondary treatment and complete aerobic treatment without primary sedimentation. Wastewater is fed continuously into an aerated tank where the microorganisms metabolize and biologically flocculate the organics. Microorganisms (activated sludge) are settled from the aerated mixed liquor under quiescent conditions in the final clarifier and returned to the aeration tank. Clear supernatant from the final settling tank is the plant effluent (Figure 73).

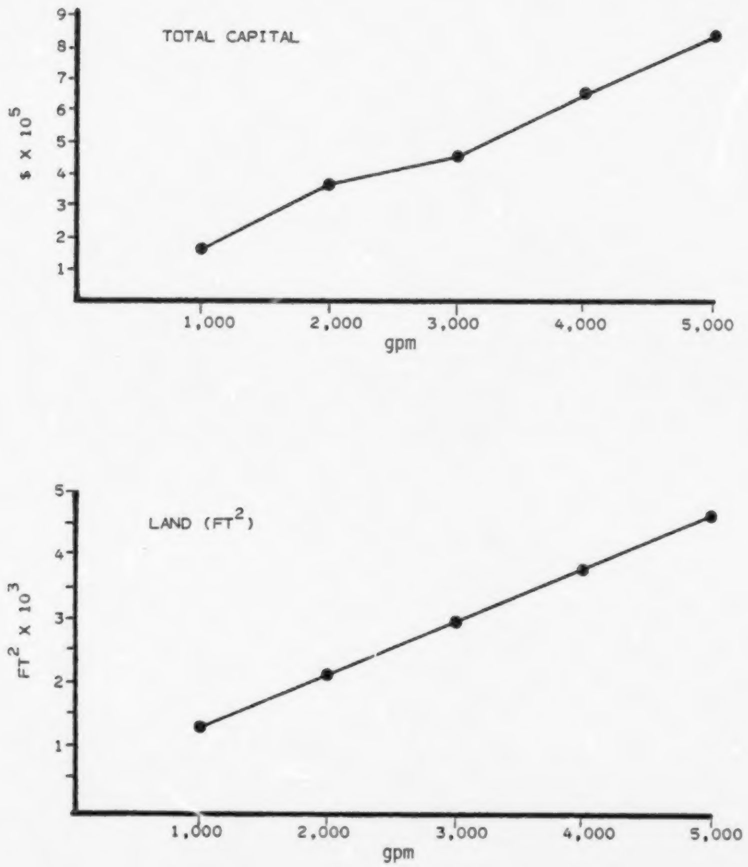

Figure 70. Carbon adsorption: changes in total capital costs with scale.

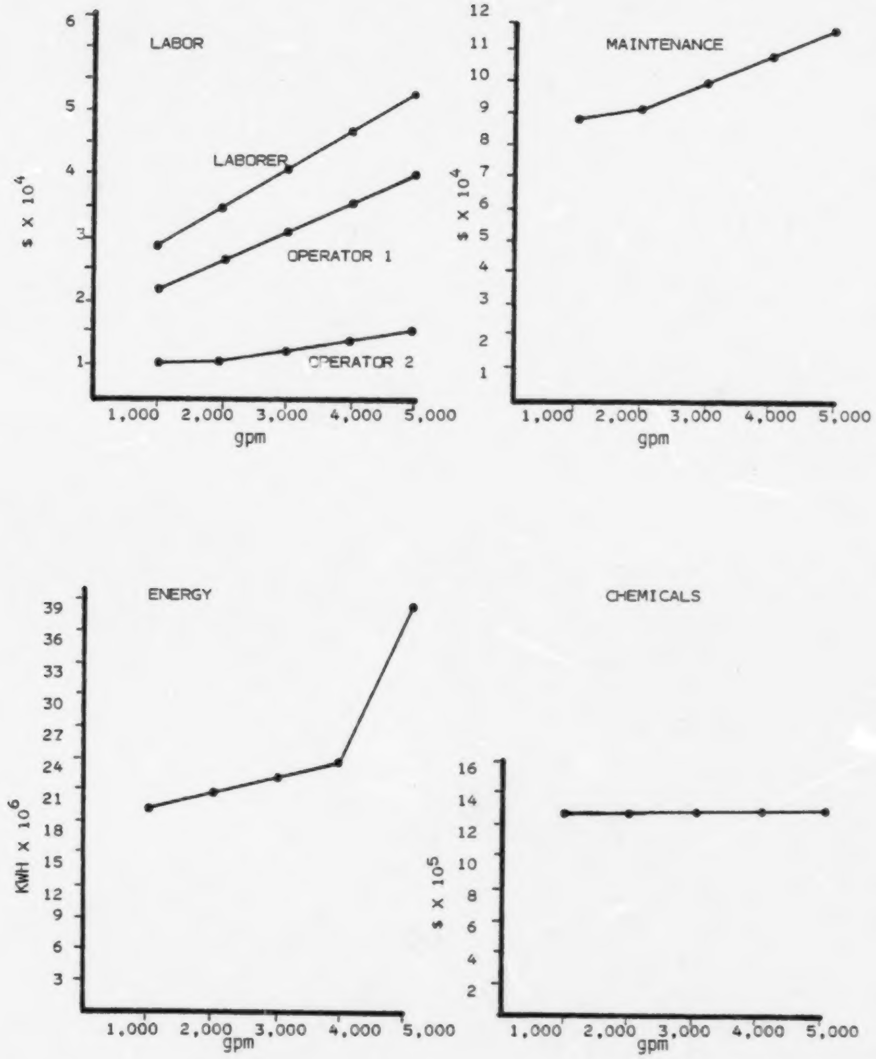

Figure 71. Carbon adsorption: changes in O&M requirements with scale.

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TABLE 54. COMPUTATION OF LIFE CYCLE AVERAGE COST FOR IMPLEMENTING CARBON ADSORPTION (LIFETIME - 7 YEARS)

Item	Direct Operating Costs*	Indirect Operating Costs†	Sum Operating Costs	Present Value Annualized Costs#	Annual Quantity of Throughput (x 1,000 Gal.)**
YEAR 1‡	3,626,418	996,992	4,623,410	4,623,410	624,000
YEAR 2	3,989,060	1,069,521	5,058,581	4,598,710	624,000
YEAR 3	4,387,966	1,149,302	5,537,268	4,576,254	624,000
YEAR 4	4,826,762	1,237,061	6,063,824	4,555,840	624,000
YEAR 5	5,309,439	1,333,596	6,643,035	4,537,282	624,000
YEAR 6	5,840,382	1,439,785	7,280,168	4,520,411	624,000
YEAR 7	6,424,421	1,556,593	7,981,014	4,505,074	624,000
TOTALS			43,187,300	31,916,981	4,368,000
Simple Average (Per 1,000 Gal.)			9.89		
Simple Average (Per Cubic Meter)			2.61		
Life Cycle Average (Per 1,000 Gal.)				7.31	
Life Cycle Average (Per Cubic Meter)				1.93	1.93

---

* Assumes 10% annual inflation.

† Inflation increases the administrative overhead only.

# Assumes a 10% interest/discount rate to the beginning of the first year of operation.

** 5,000 GPM x 60 min x 8 hrs/day x 260 days/yr.

‡ First year costs in mid-1978 dollars - for Chicago example.

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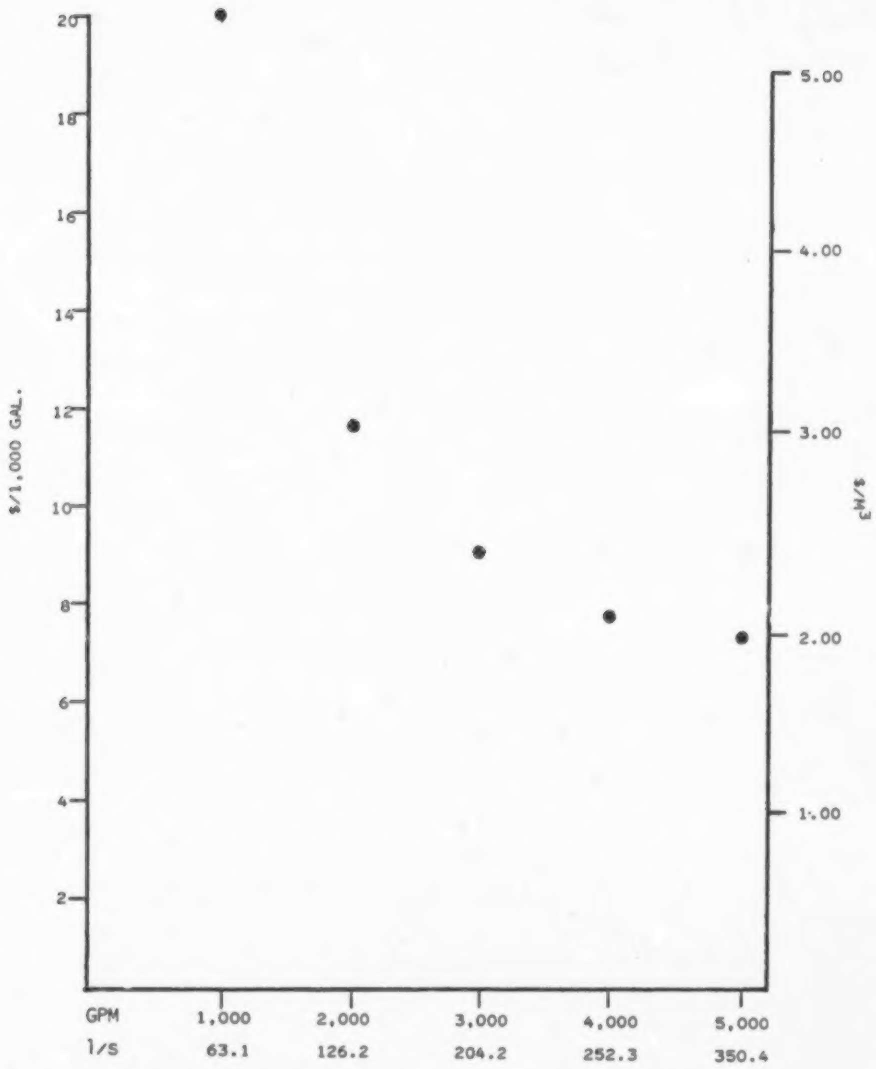
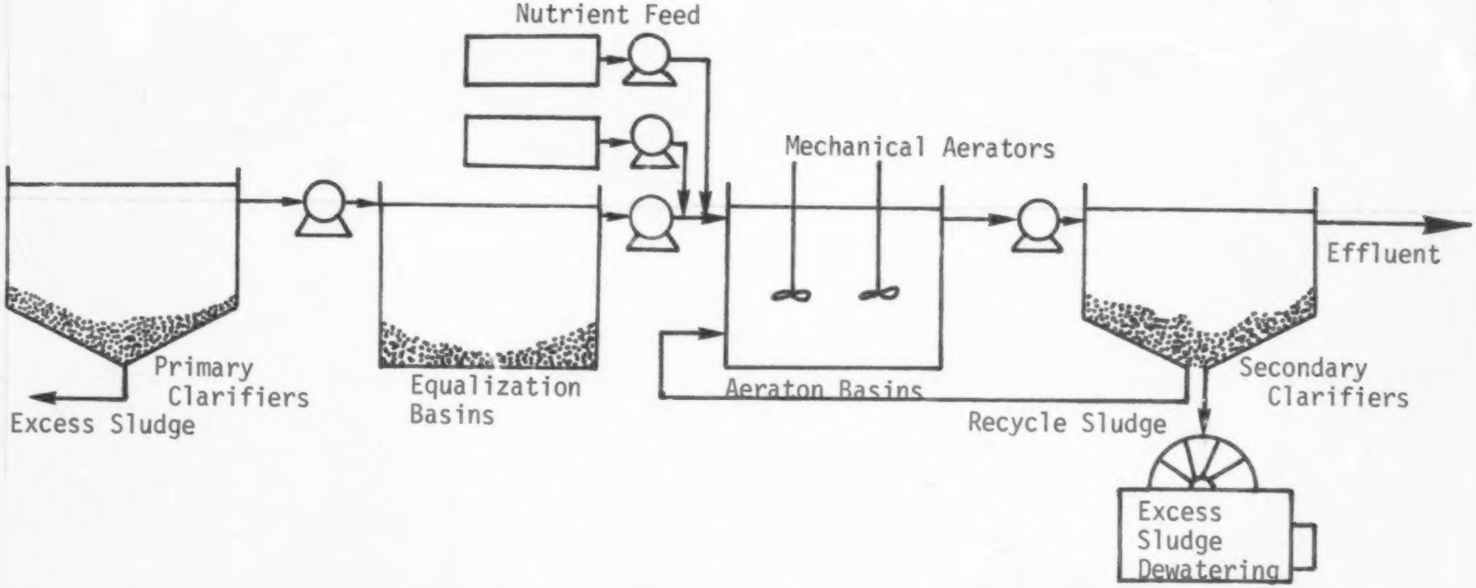


Figure 72. Carbon adsorption: life cycle costs at five scales of operation.



Nutrient Feed
Mechanical Aerators
Effluent
Primary Clarifiers
Excess Sludge
Equalization Basins
Aeraton Basins
Recycle Sludge
Secondary Clarifiers
Excess Sludge Dewatering

Figure 73. Activated sludge process: flow diagram.

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Microbial growth in the mixed liquor is maintained in the declining or endogenous growth phase to insure good settling characteristics. Synthesis of the waste organics results in a buildup of the microbial mass in the system. Excess activated sludge is wasted from the system to maintain the proper food-to-microorganism ratio to insure optimum operation.

Activated sludge is truly an aerobic treatment process, since the biological floc are suspended in a liquid medium containing dissolved oxygen. Aerobic conditions must be maintained in the aeration tank; however, in the final clarifier, the dissolved oxygen concentration can become extremely low. Dissolved oxygen extracted from the mixed liquor is replenished by air supplied to the aeration tank (25, 26).

Unit processes included in this technology are:

- Sedimentation basin
- Aeration basin
- Clarifier
- Sludge dewatering
- Chemical storage

Changes in Configuration with Scale

Additional, parallel equal-sized modules are included for increased flow rates. The equations in Appendix F describe how the unit processes are sized according to flow and waste loadings.

Applications

Biodegradable organic constituents in waste streams associated with the organic chemicals industry (Appendix E).

Costs

The capital and O&M unit cost files (Appendices B and C) are used together with the cost equations in Appendix F to derive capital and first year operating costs for activated sludge (Tables 55 and 56). All costs are adjusted for inflation to mid-1978 values and are based on charges as they exist in the City of Chicago, Illinois.

The breakdown of capital costs for activated sludge shows that the sedimentation basin, sludge dewatering and chemical storage/feed facilities are the most expensive unit processes. The major O&M costs are for labor and chemicals. The total capital and first year operating costs are $4,329,039 and $2,188,214 for the 5,000 gpm example facility.

The change in total capital costs (excluding land costs) according to the scale of operation is shown in Figure 74.

TABLE 55. SUMMARY OF CAPITAL COSTS FOR ACTIVATED SLUDGE*

Capital Cost Category Module	Costs†						
	Site Preparation	Structures	Mechanical Equipment	Electrical Equipment	Land	Total	Other Land (ft^2)
Sedimentation Basin	$ 29,700	$ 241,000	$ 766,000	$ 2,020	$ 25,500	---	34,300
Aerated basin	10,500	116,000	171,000	---	12,800	---	17,200
Clarifier	995	115,000	22,300	172	645	---	867
Sludge dewatering	178	42,600	919,000	9,190	4,120	---	5,530
Chemical feed	14,710	213,000	935,000	---	6,220	---	8,362
Chemical feed	8,330	107,000	29,500	---	1,520	---	2,039
Chemical pump	---	---	1,530	---	---	---	---
Chemical pump	---	---	1,470	---	---	---	---
Waste pump	---	---	10,800	---	---	---	---
Waste pump	---	---	10,800	---	---	---	---
Sludge pump	---	---	4,490	---	---	---	---
Yard piping	900	---	55,200	---	---	---	---
Total	65,313	834,600	2,927,090	11,382	50,805	---	68,298
Supplemental capital costs	---	141,303#	---	---	---	---	---
Subtotal of capital costs	---	---	---	---	---	4,030,493	---
Working capital**	---	---	---	---	---	97,021	---
AFDC ǂ	---	---	---	---	---	201,525	---
Grand total of capital costs	---	---	---	---	---	4,329,039	---

* Scale = 5,000 gpm; total nitrogen = 2.0 ppm; total phosphorus = 1.0 ppm, BOD = 150.

† Mid-1978 dollars.

Building.

** At one month of direct operating costs.

ǂ Allowance for funds during construction at 5% of capital costs.

TABLE 56. SUMMARY OF FIRST YEAR O&M COSTS FOR ACTIVATED SLUDGE*

O&M Cost Category Module	Costs † Labor Type 1 Operator 1 ($7.77/hr)	Type 2 Operator 2 ($9.19/hr)	Type 3 Laborer ($6.76/hr)	Energy Electrical ($0.035/KWH)	Maintenance Costs	Chemical Costs	Total	Other KWH (yr)
Sedimentation basin	$3,911	$ 276	$ 40,850	$ 102	$ 68,600	$ ----	---	2,914
Aerated basin	3,521	831	33,686	3,790	34,100	----	---	103,286
Clarifier	10,636	755	111,078	102	2,230	----	---	2,914
Sludge dewatering	2,933	900	30,637	70,500	9,240	2,020	---	2,014,285
Chemical feed	--	--	---	---	900	699,000	---	---
Chemical feed	--	--	---	---	800	8,740	---	---
Chemical pump	--	--	---	35	---	----	---	1,000
Chemical pump	--	--	---	17	---	----	---	486
Waste pump	--	--	---	8,630	---	----	---	246,571
Waste pump	--	--	---	8,630	---	----	---	246,571
Sludge pump	--	--	---	4,490	---	----	---	128,286
Yard piping	--	--	179	---	363	----	---	---
Total	21,001	2,762	216,430	96,296	116,233	709,760	---	2,751,313
Supplemental O&M costs	--	--	---	---	1,770	----	---	---
Subtotal of direct O&M costs	--	--	---	---	---	----	$ 1,164,252	---
Administrative overhead#	--	--	---	---	---	----	232,850	---
Debt service and amortization **	--	--	---	---	---	----	704,531	---
Real estate taxes and insurance ǂ	--	--	---	---	---	----	86,581	---
Total first year operating costs	--	--	---	---	---	----	2,188,214	----

* Scale = 5,000 gpm.

† Mid-1978 dollars.

# At 20% of direct operating costs.

** At 10% interest over 10 years.

ǂ At 2% of total capital.

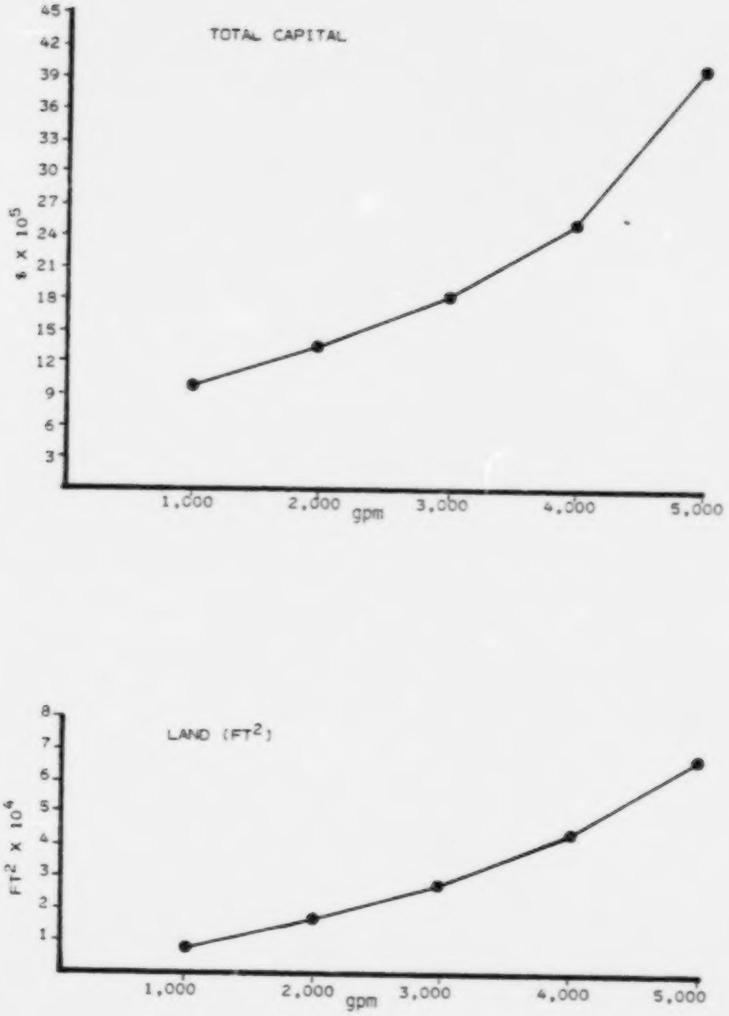

Figure 74. Activated sludge: changes in total capital costs with scale.

The capital cost per 1,000 gallons of waste treated is \$7.50 at 1,000 gpm. This decreases to \$4.92 at 3,000 gpm and then increases to \$6.38 at 5,000 gpm.

Activated sludge O&M requirements are shown in Figure 75. Labor and maintenance costs demonstrate significant economies of scale, while power requirements are constant throughout the range.

The direct and indirect operating costs (including debt service and amortization) are used to calculate the average cost over the 10-year life cycle of the 5,000 gpm activated sludge facility. The life cycle average cost is \$3.10/1,000 gal (\$0.81/m^3). Figure 76 shows the life cycle average costs at five different scales of operation.

EVAPORATION POND

Description

In arid regions, where evaporation rates are much greater than the amount of rainfall, evaporation ponds are used for volume reduction and disposal of industrial effluents. As shown in Figure 77 , the pond must have sufficient volume to retain the waste volume plus additional rainfall.

Wastes are introduced into the pond and retained for an indefinite period of time. Water and other volatile components are allowed to evaporate off, and less volatile compounds and salts remain behind. The pond is periodically cleaned out, and resulting sludges are disposed. In many cases, the evaporation pond is present at a larger land disposal facility. After sufficient solids buildup, the pond is covered over with soil and relocated.

Changes in Configuration with Scale

There is no significant design change with scale. The limiting factor is land since evaporation efficiencies are directlv related to the surface area.

Applications

The evaporation pond is useful in dewatering of aqueous wastes containing metal or other inorganic salts. Increasing regulation of air emissions has limited its applicability to disposal of less volatile organic compounds only.

Costs

Summaries of capital and first year operating costs for

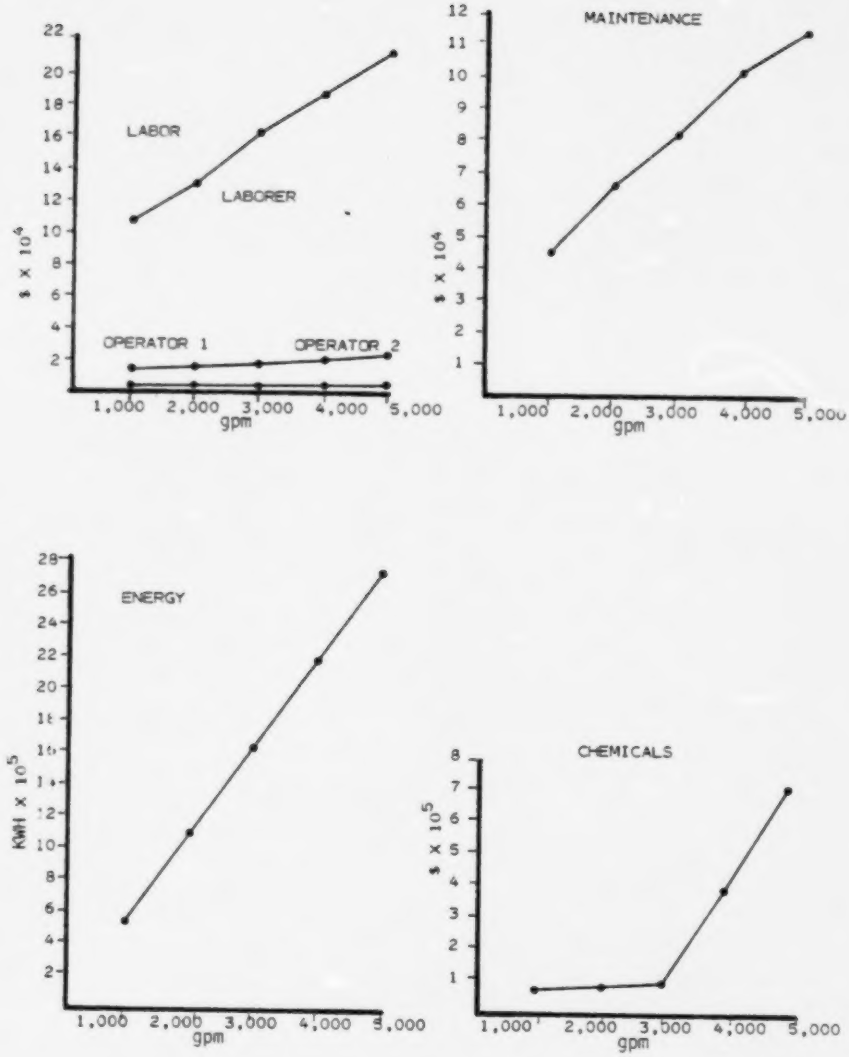

Figure 75. Activated sludge: changes in O&M requirements with scale.

TABLE 57. COMPUTATION OF LIFE CYCLE AVERAGE COST FOR IMPLEMENTING ACTIVATED SLUDGE (LIFETIME - 10 YEARS)

Item	Direct Operating Costs*	Indirect Operating Costs†	Sum Operating Costs	Present Value Annualized Costs#	Annual Quantity of Throughput (x 1,000 Gal.)**
YEAR 1‡	1,164,252	1,023,962	2,188,214	2,188,214	624,000
YEAR 2	1,280,677	1,047,247	2,327,925	2,116,295	624,000
YEAR 3	1,408,745	1,072,861	2,481,606	2,050,914	624,000
YEAR 4	1,549,619	1,101,036	2,650,655	1,991,476	624,000
YEAR 5	1,704,581	1,132,028	2,836,610	1,937,442	624,000
YEAR 6	1,875,039	1,166,120	3,041,159	1,888,321	624,000
YEAR 7	2,062,543	1,203,621	3,266,164	1,843,664	624,000
YEAR 8	2,268,798	1,244,871	3,513,669	1,803,068	624,000
YEAR 9	2,495,678	1,290,247	3,785,925	1,766,162	624,000
YEAR 10	2,745,245	1,340,161	4,085,406	1,732,611	624,000
TOTALS			30,177,333	19,318,167	6,240,000
Simple Average (Per 1,000 Gal.)			4.84		
Simple Average (Per Cubic Meter)			1.28		
Life Cycle Average (Per 1,000 Gal.)				3.10	
Life Cycle Average (Per Cubic Meter)				0.81	

* Assumes 10% annual inflation.

† Inflation increases the administrative overhead only.

# Assumes a 10% interest/discount rate to the beginning of the first year of operation.

** 5,000 GPM x 60 min x 8 hrs/day x 260 days/yr.

‡ First year costs in mid-1978 dollars - for Chicago example.

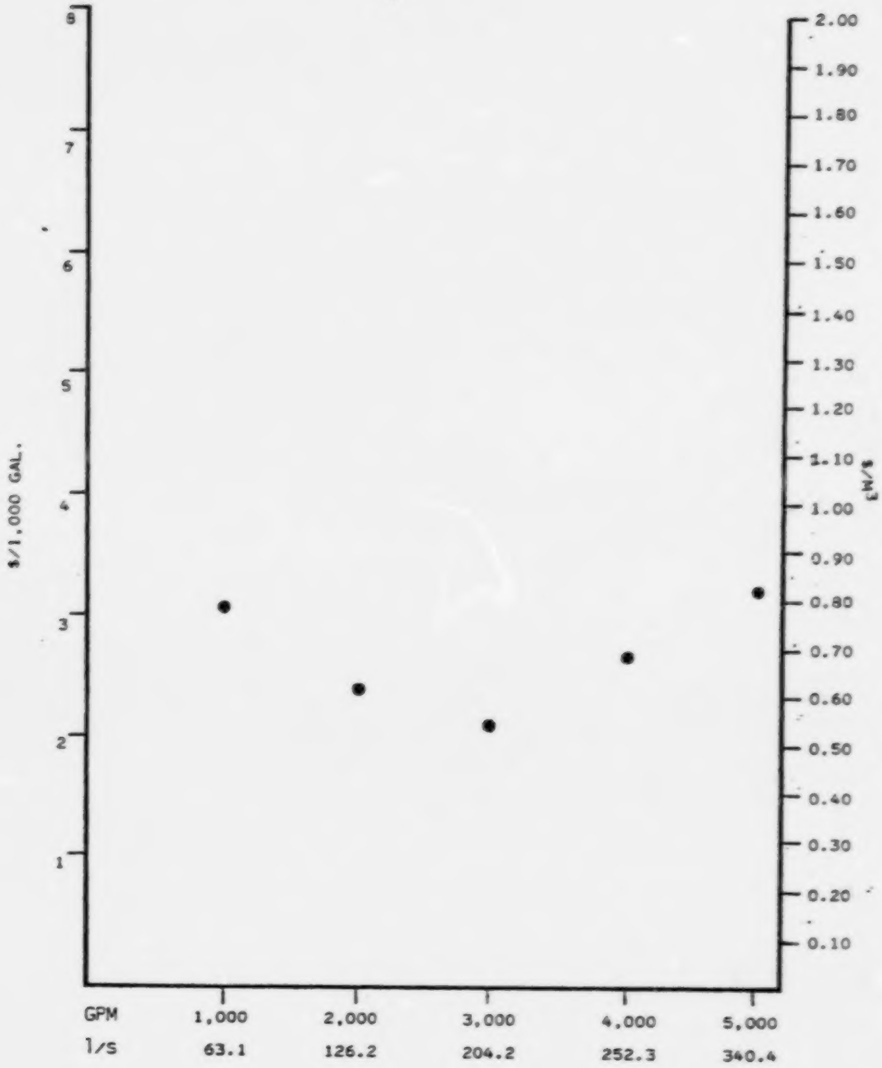

Figure 76. Activated sludge: life cycle costs at five scales of operation.

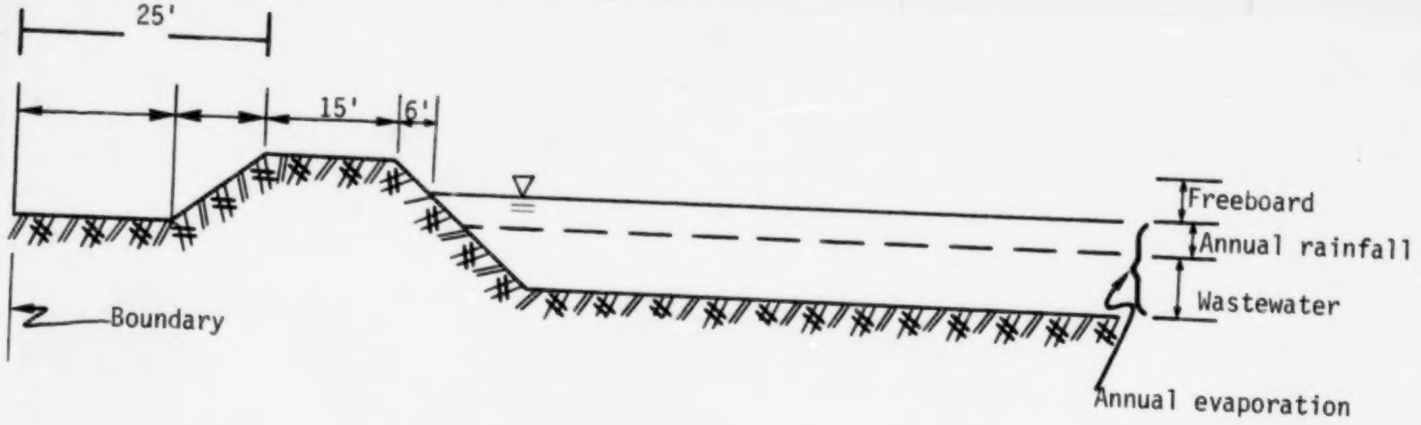
25'
15'
6'
Boundary
Freeboard
Annual rainfall
Wastewater
Annual evaporation

Figure 77. Evaporation pond: flow diagram and levee configuration.

evaporation pond are shown in Tables 58 and 59. These estimates are based on mid-1978 costs for components, unit processes, labor, utilities, etc., as applicable in Chicago, Illinois. The estimates are based on the cost files in Appendices B and C, and the cost equations included in Appendix F.

As shown in Table 58, the most costly elements of evaporation pond acquisition and construction are site preparation (pond excavation and levee construction), land and the pond liner. The construction of ponds where natural clay layers can serve as liners would significantly reduce the capital expense. The use of natural depressions or areas already excavated for landfill cover can also reduce site preparation costs.

The O&M requirements for evaporation pond are small compared to other treatment/disposal technologies. The largest annual expenditure is $75,534 for the labor staff. Maintenance costs are low due to the absence of complicated mechanical equipment. The only energy costs are those for waste pumping.

Figure 78 shows the capital costs (exclusive of land costs) for five scales of operation and the corresponding land area requirements. The capital costs demonstrate only small economies of scale ($42.89 versus $41.35/1,000 gal at 1,000 and 5,000 gpm, respectively). This is due to the dominance of total capital cost by the site preparation costs. Because pond depth and retention time are held constant, pond area (and hence site preparation cost) is directly related to the imput flow rate.

The O&M requirements for evaporation pond as a function of scale are shown in Figure 79. Although labor, maintenance and energy all demonstrate significant economies of scale, their absolute values are small in comparison to the capital costs. There are, therefore, no economies of scale evidenced in the life cycle average cost analysis.

The average cost of the 5,000 gpm facility, over a 20-year life cycle, is $3.52/1,000 gal ($0.94/m^3) (Table 60). The life cycle average cost at five scales of operation is shown in Figure 80. The data reflect the dominance of site preparation costs over the entire range studied.

INCINERATION

Description

The rotary kiln incineration process selected as the model for incineration is a versatile unit that can be used to dispose of solid, liquid, and gaseous combustible wastes. They have been utilized both in industrial and municipal installations. Applications of rotary kiln incineration to the disposal of obsolete chemical warfare agents and munitions have been reported.

TABLE 58. SUMMARY OF CAPITAL COSTS FOR EVAPORATION POND*

	Costs†								Quantities	
Capital cost Category Module	Site Preparation	Structures	Mechanical Equipment	Electrical Equipment	Land	Other	Total	Land	Other	Other
Evaporation pond	$22,875,000	$ ---	$ ---	$ ---	$ 4,620,000	$2,732,400	---	6.21×10^6	9.62×10^6	7.2×10
Waste pump	---	---	10,800	---	---	---	---	---	---	---
Yard piping	675	---	39,300	---	---	---	---	---	---	---
Total	22,875,675	---	50,100	---	4,620,000	2,732,400	---	6.21×10^6	9.62×10^6	7.2×10
Supplemental capital costs	---	141,303 #	---	---	---	---	---	---	---	---
Subtotal of capital costs	---	---	---	---	---	---	$ 30,419,478	---	---	---
Working capital**	---	---	---	---	----	----	10,684	---	---	---
AFDC‡	---	---	---	---	----	----	1,520,974	---	---	---
Grand total of capital costs	---	---	---	---	----	----	31,951,136	---	---	---

* Scale = 5,000 gpm; batch treatment (30-day retention); evaporation/rainfall ratio is 2:1.

† Mid-1978 dollars.

Building.

** At one month of direct operating costs.

‡ Allowance for funds during construction at 5% of capital costs.

TABLE 59. SUMMARY OF FIRST YEAR O&M COSTS FOR EVAPORATION POND*

O&M Cost Category Module	Costs† Labor Type 1 Operator 1 ($7.77/hr)	Type 2 Operator 2 ($9.19/hr)	Type 3 Laborer ($6.76/hr)	Energy Electrical ($0.035/KWH)	Maintenance Costs	Total
Evaporation pond	$27,551	$14,327	$ 75,380	$ ---	$ -----	---
Waste pump	---	---	---	8,630	203	---
Yard piping	---	---	154	---	197	---
Total	27,551	14,327	75,534	8,630	400	
Supplemental O&M costs	---	---	---	---	1,770	---
Subtotal of direct O&M costs	---	---	---	---	----	$ 128,212
Administrative overhead**	---	---	---	---	----	25,642
Debt service and amortization	---	---	---	---	----	3,752,968
Real estate taxes and insurance ‡	---	---	---	---	----	639,023
Total first year operating costs	---	---	---	---	----	4,545,845

* Scale = 5,000 gpm; batch treatment (30-day retention); rainfall ratio 2:1.
† Mid-1978 dollars.
# At 20% of direct operating costs.
** At 10% interest over 20 years.
‡ At 2% of total capital.

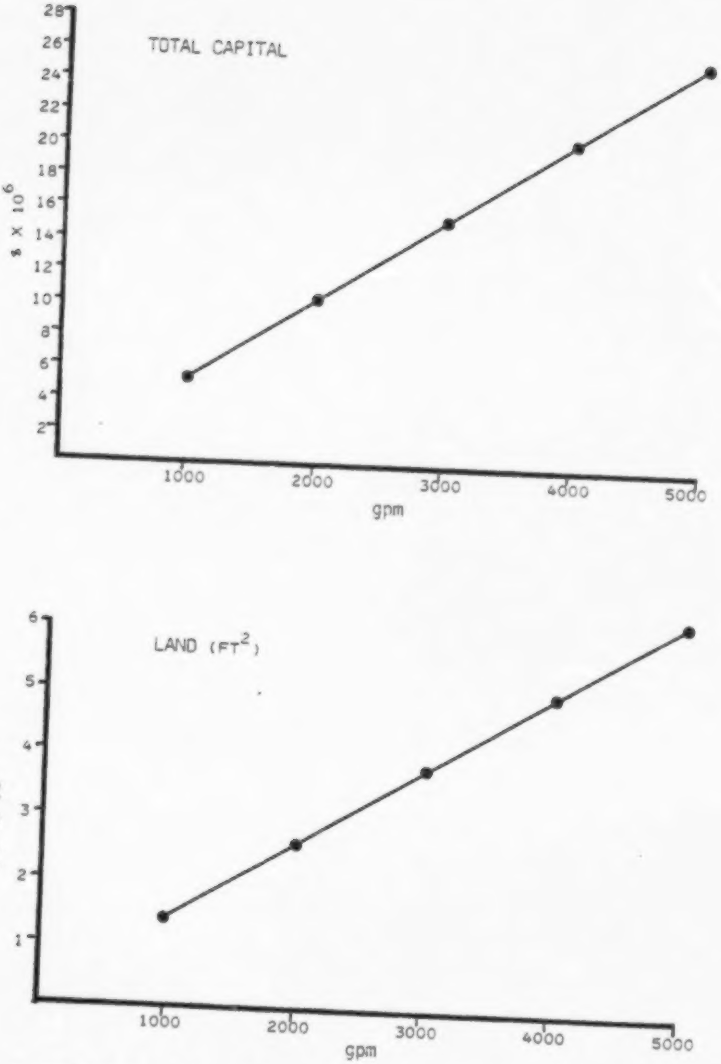

Figure 78. Evaporation pond: changes in total capital costs with scale.

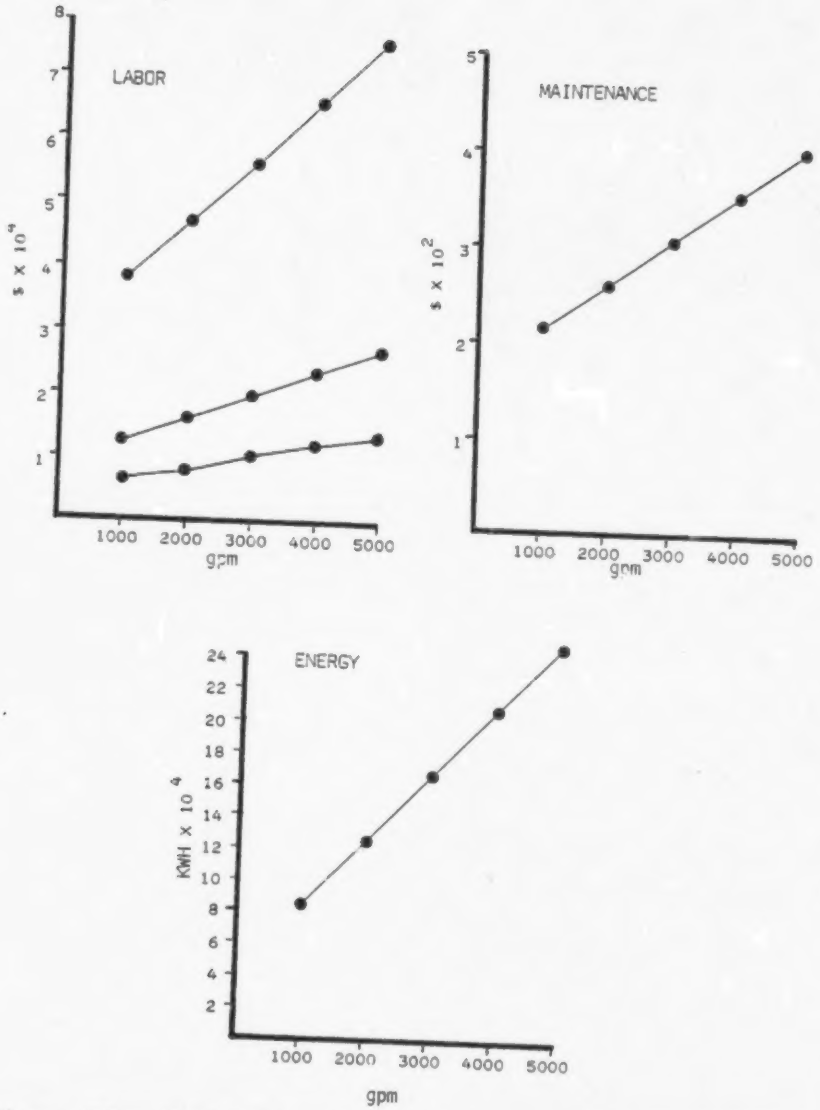

Figure 79. Evaporation pond: changes in O&M requirements with scale.

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TABLE 60. COMPUTATION OF LIFE CYCLE AVERAGE COST FOR IMPLEMENTING EVAPORATION POND (LIFETIME - 20 YEARS)

Item	Direct Operating Costs*	Indirect Operating Costs†	Sum Operating Costs	Present Value Annualized Costs#	Annual Quantity of Throughput (x 1,000 Gal.)**
YEAR 1‡	128,212	4,417,634	4,545,846	4,545,846	624,000
YEAR 2	141,033	4,420,198	4,561,231	4,146,574	624,000
YEAR 3	155,137	4,423,019	4,578,155	3,783,599	624,000
YEAR 4	170,650	4,426,121	4,596,771	3,453,622	624,000
YEAR 5	187,715	4,429,534	4,617,249	3,153,643	624,000
YEAR 6	206,487	4,433,289	4,639,775	2,880,935	624,000
YEAR 7	227,135	4,437,418	4,664,554	2,633,019	624,000
YEAR 8	249,849	4,441,961	4,691,810	2,407,640	624,000
YEAR 9	274,834	4,446,958	4,721,792	2,202,751	624,000
YEAR 10	302,317	4,452,455	4,754,772	2,016,487	624,000
YEAR 11	332,549	4,458,501	4,791,050	1,847,157	624,000
YEAR 12	365,804	4,465,152	4,830,956	1,693,221	624,000
YEAR 13	402,384	4,472,468	4,874,852	1,553,278	624,000
YEAR 14	442,623	4,480,516	4,923,138	1,426,058	624,000
YEAR 15	486,885	4,489,368	4,976,253	1,310,403	624,000
YEAR 16	535,573	4,499,106	5,034,679	1,205,262	624,000
YEAR 17	589,131	4,509,817	5,098,948	1,109,680	624,000
YEAR 18	648,044	4,521,600	5,169,644	1,022,786	624,000
YEAR 19	712,848	4,534,561	5,247,409	943,793	624,000
YEAR 20	784,133	4,548,818	5,332,951	871,980	624,000
TOTALS			96,651,835	44,207,734	12,480,000
Simple Average (Per 1,000 Gal.)			7.75	ok	
Simple Average (Per Cubic Meter)			2.05	.05	
Life Cycle Average (Per 1,000 Gal.)				3.54	ok
Life Cycle Average (Per Cubic Meter)				0.94	0.94

---

* Assumes 10% annual inflation.

† Inflation increases the administrative overhead only.

# Assumes a 10% interest/discount rate to the beginning of the first year of operation.

** 5,000 GPM x 60 min x 8 hrs/day x 260 days/yr.

‡ First year costs in mid-1978 dollars - for Chicago example.

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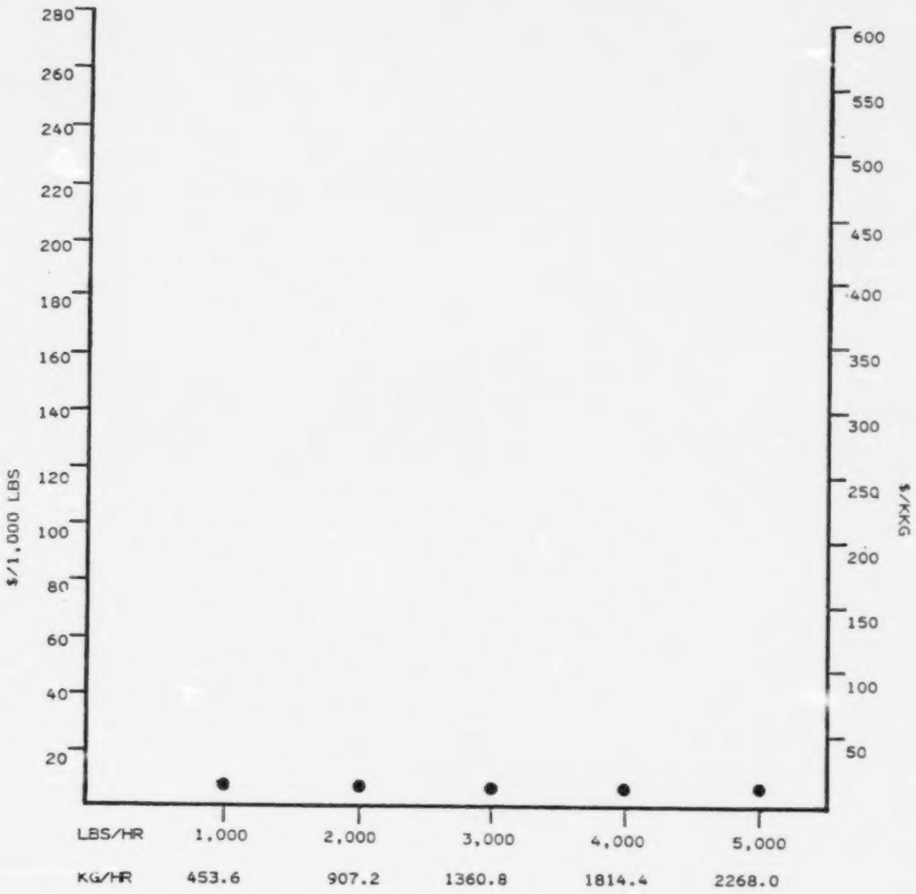

Figure 80. Evaporation pond: life cycle costs at five scales of operation (assuming waste specific gravity = 1).

The rotary kiln incinerator is a cylindrical shell lined with firebrick or other refractory and mounted with its axis at a slight slope from the horizontal. It is a highly efficient unit when applied to solids, liquids, sludges and tars because of its ability to attain excellent mixing of unburned waste and oxygen as it revolves. The incinerator costed here includes the secondary burner and scrubber.

Rotary kiln incinerators, when applied to industrial (includes military) applications, are generally designed to accept both solid and liquid feed. A typical unit is shown in Figures 81 and 82. Liquid waste transported to the incinerator is transferred to receiving tanks and then strained as it is pumped into a burning tank, where it is blended with auxiliary fuel for optimum burning characteristics. All liquid residues are burned in suspension by atomization with steam or air. All refuse is removed for disposal in a secure landfill (27).

Changes in Configuration with Scale

A single rotary kiln incinerator such as that shown in Figures 81 and 82 can accommodate a feed rate of up to 700 lb/hr. Scales of operation above this will require additional waste storage and/or incineration capacity. Although waste storage facilities are provided to equalize disruptions in input flow, it is assumed that the average storage input rate equals the incinerator charging rate. Appendix F includes the cost equations for waste storage.

Applications

See Appendix E for a list of chemicals and chemical wastes that can be disposed of by incineration.

Costs

Capital costs for incineration are itemized in Table 61 for an example 1,000 lb/hr facility. The incinerator (including mechanical and electrical equipment) costs $580,000 and the waste storage facilities (including structures and mechanical equipment) cost $524,300. The total capital cost for the 1,000 lb/hr facility is $1,345,149 (mid-1978 dollars).

Table 62 summarizes the first-year operating costs for the example incineration facility. The major operating cost is for labor (Operator-1 level comprises almost 40 percent of the subtotal direct O&M costs). The total first-year operating cost, including administrative overhead ($34,877), debt service and amortization ($354,847) and real estate taxes and insurance ($26,903), is $597,014.

Figure 83 shows the capital costs (excluding land costs)

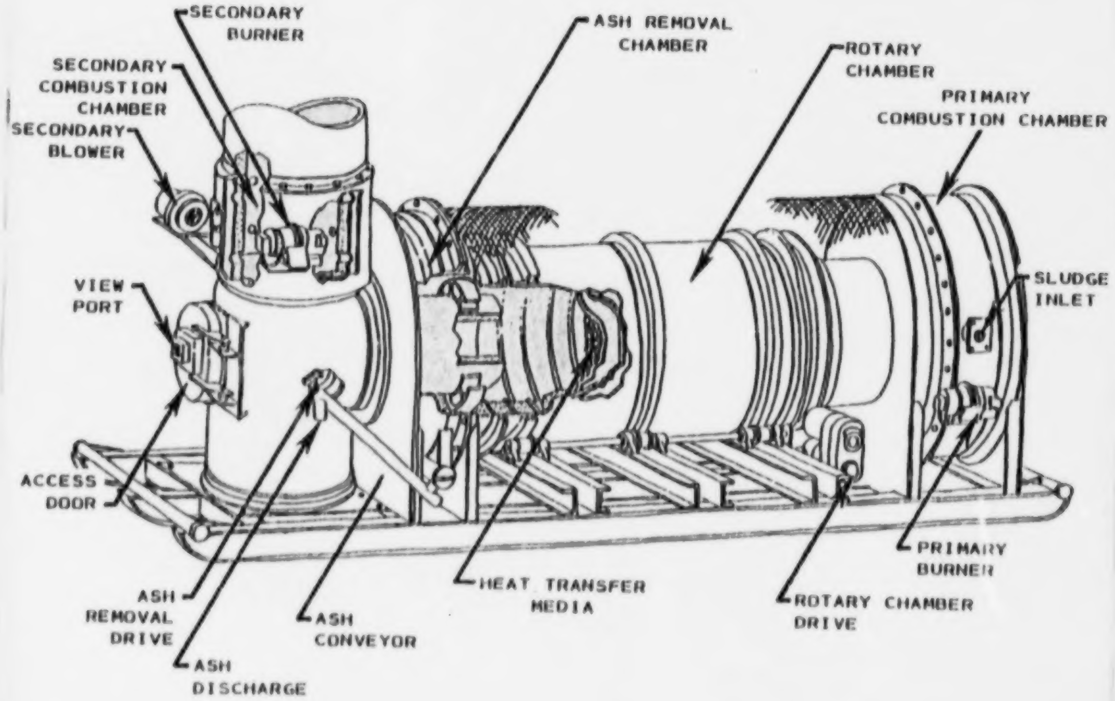
SECONDARY BURNER
SECONDARY COMBUSTION CHAMBER
SECONDARY BLOWER
ASH REMOVAL CHAMBER
ROTARY CHAMBER
PRIMARY COMBUSTION CHAMBER
SLUDGE INLET
VIEW PORT
ACCESS DOOR
ASH REMOVAL DRIVE
ASH DISCHARGE
ASH CONVEYOR
HEAT TRANSFER MEDIA
ROTARY CHAMBER DRIVE
PRIMARY BURNER

Figure 81. React-O-Therm Rotary Kiln Sludge Incinerator (Cutaway View).

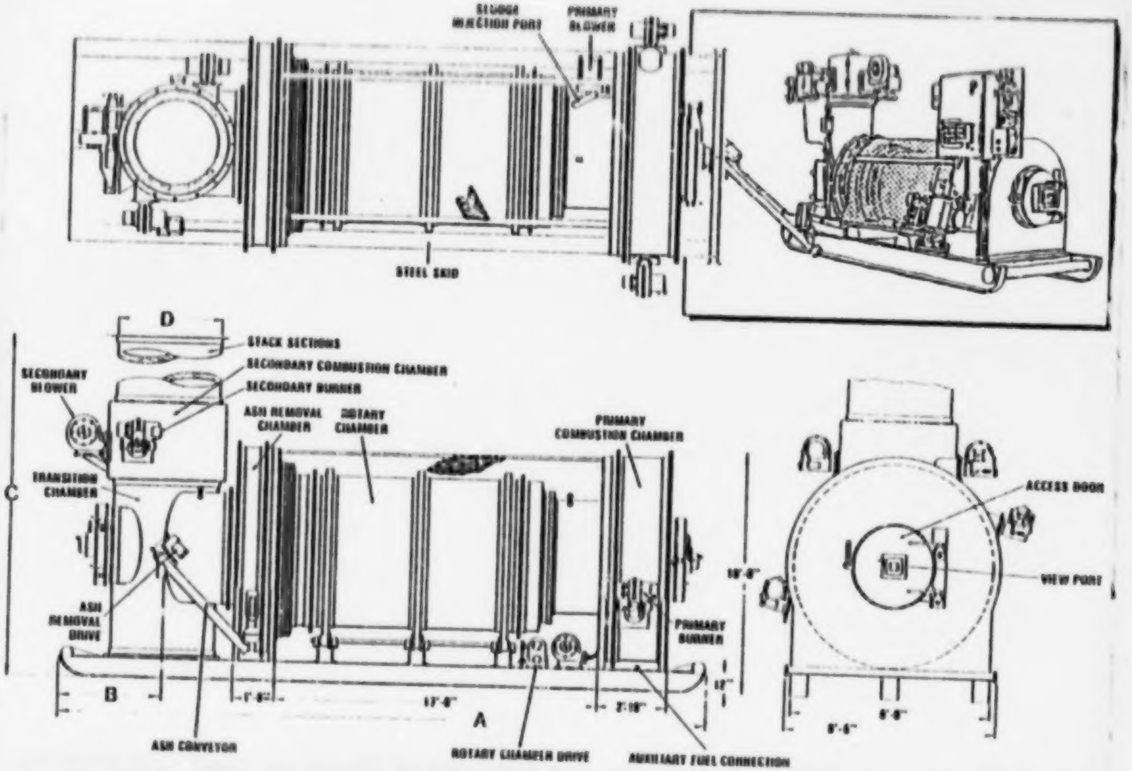
SLUDGE INJECTION PORT
PRIMARY BLOWER
STEEL SKID
D
STACK SECTIONS
SECONDARY COMBUSTION CHAMBER
SECONDARY BURNER
SECONDARY BLOWER
ASH REMOVAL CHAMBER
ROTARY CHAMBER
PRIMARY COMBUSTION CHAMBER
TRANSITION CHAMBER
C
ASH REMOVAL DRIVE
B
1'-8"
17'-0"
A
2'-10"
12"
10'-0"
PRIMARY BURNER
ASH CONVEYOR
ROTARY CHAMBER DRIVE
AUXILIARY FUEL CONNECTION
ACCESS DOOR
VIEW PORT
8'-0"
8'-6"

Figure 82. React-O-Therm Rotary Kiln Sludge Incinerator (side and plan view).

TABLE 61. SUMMARY OF CAPITAL COSTS FOR INCINERATION*

Capital Cost Category Module	Costs †						Other Land (ft^2)
	Site Preparation	Structures	Mechanical Equipment	Electrical Equipment	Land	Total	
Incineration	$ 310	$ 6,840	$ 435,000	$ 145,000	$ 893	---	1,200
Waste pump	---	---	2,950	---	---	---	---
Waste storage	31,240	427,000	97,300	---	23,000	---	30,980
Total	31,550	433,840	535,250	145,000	23,893	---	32,180
Supplemental capital costs	---	97,324#	---	---	---	---	---
Subtotal of capital costs	---	---	---	---	---	$ 1,266,857	---
Working capital**	---	---	---	---	---	14,949	---
AFDC ‡	---	---	---	---	---	63,343	---
Grand total of capital costs	---	---	---	---	---	1,345,149	---

* Scale = 1,000 lb/hr.

† Mid-1978 dollars.

# Building.

** At one month of direct operating costs.

‡ Allowance for funds during construction at 5% of capital costs.

TABLE 62. SUMMARY OF FIRST YEAR O&M COSTS FOR INCINERATION*

	Costs						
	Labor						
O&M Cost Category Module	Type 1 Operator 1 ($7.77/hr)	Type 2 Operator 2 ($9.19/hr)	Type 3 Laborer ($6.76/hr)	Energy Electrical ($0.035/KWH)	Maintenance Costs	Total	Other KWH (yr)
Incinerator	$70,713	$ 31,347	$ 10,279	$ 10,200	$ 52,770	---	270,000
Waste pump	---	---	---	1,730	---	---	---
Waste storage	---	---	---	---	1,000	---	---
Total	70,713	31,347	10,279	11,930	53,770	---	270,000
Supplemental O&M costs	---	---	---	---	1,348	---	---
Subtotal of direct O&M costs	---	---	---	---	---	$ 179,387	---
Administrative overhead#	---	---	---	---	---	35,877	---
Debt service and amortization**	---	---	---	---	---	354,847	---
Real estate taxes and insurance ‡	---	---	---	---	---	26,903	---
Total first year operating costs	---	---	---	---	---	597,014	---

† Mid-1978 dollars.
# At 20% of direct operating costs .
** At 10% interest over 5 years.
‡ At 2% of total capital.

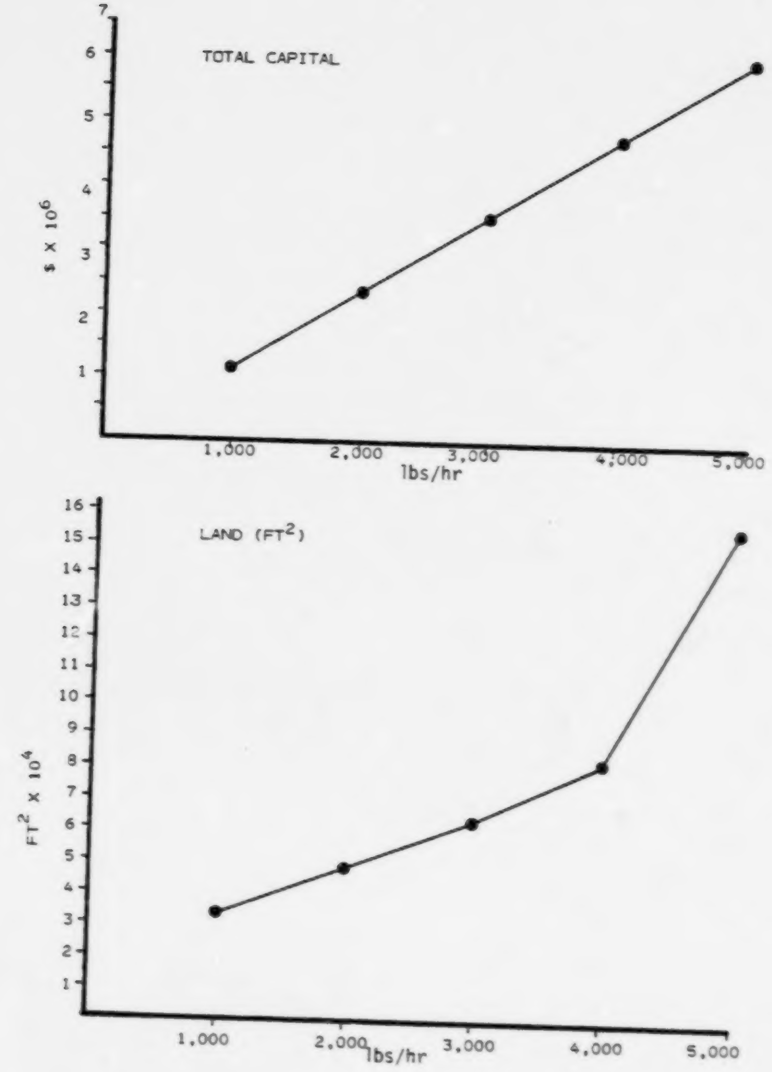

Figure 83. Incineration: changes in total capital costs with scale.

for five scales of operation and the corresponding land requirements for incineration. The capital cost per 1,000 lbs of waste incinerated is $597.60 at 1,000 lbs/hr and then decreases to $586.80 at 2,000 lbs/hr and maintains approximately that cost throughout the range.

The O&M requirements for incineration as a function of scale are shown in Figure 84. Total labor costs are $112,339 and $223,907 at 1,000 and 5,000 lb/hr, respectively. A significant portion of these costs are attributable to the Operator-1 labor category. Maintenance and energy requirements are constant throughout the range. The maintenance costs are equal to $25.20/1,000 lbs and the energy requirements are equal to 129.60 kwh/1,000 lbs at all scales of operation.

The average cost of the example facility, over a life cycle of 5 years, is calculated in Table 63. The life cycle average cost for the 1,000 lbs/hr facility is $256.55/1,000 lbs ($565.70/t). Figure 85 shows the life cycle average cost at five scales of operation. The analysis reflects the small economy of scale between 1,000 and 2,000 lbs/hr and the constant unit costs thereafter.

Equipment included in incineration is as follows:

- Rotary kiln with ash removal and burner
- Combustion air blower
- Atomizing air compressor
- Afterburner with burner and accessories
- Scrubbing system with pumps, fan, and all accessories
- Stack
- Instrumentation and controls.

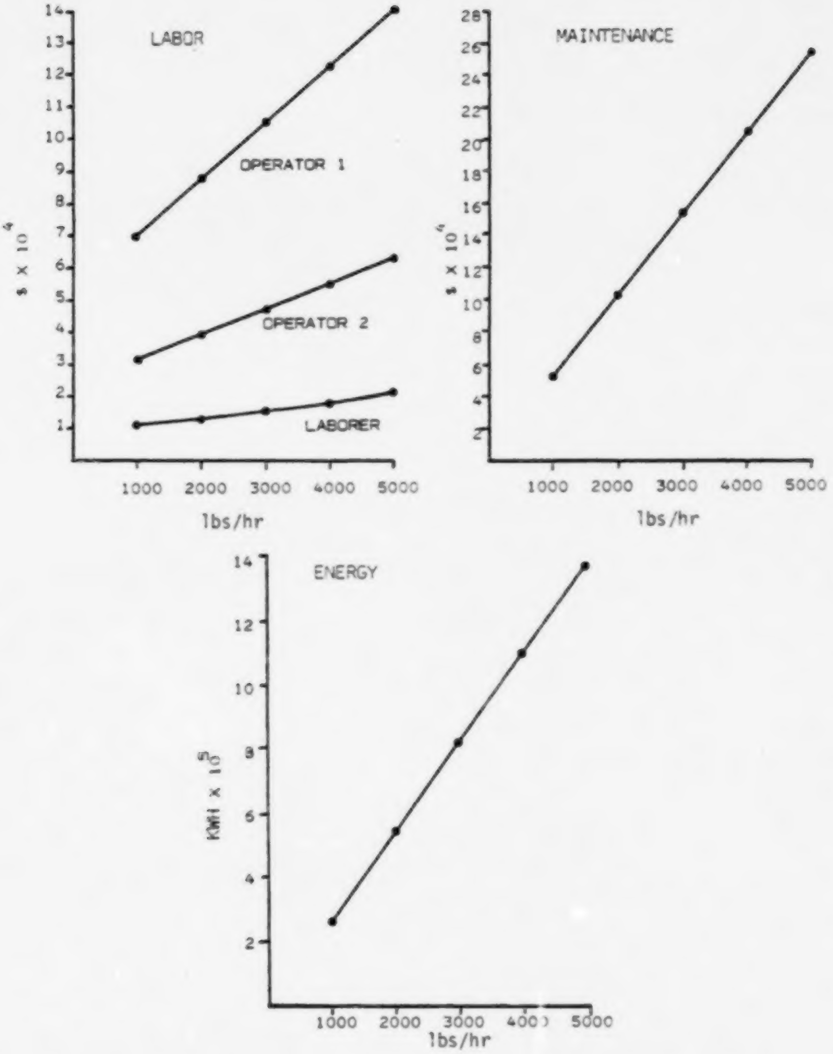

Figure 84. Incineration: changes in O&M requirements with scale.

TABLE 63. COMPUTATION OF LIFE CYCLE AVERAGE COST FOR IMPLEMENTING INCINERATION (LIFETIME - 5 YEARS)

Item	Direct Operating Costs*	Indirect Operating Costs†	Sum Operating Costs	Present Value Annualized Costs#	Annual Quantity of Throughput (x 1,000 lbs)**
YEAR 1‡	179,387	417,627	597,014	597,014	2,080
YEAR 2	197,326	421,215	618,541	562,310	2,080
YEAR 3	217,058	425,161	642,219	530,760	2,080
YEAR 4	238,764	429,502	668,266	502,078	2,080
YEAR 5	262,641	434,278	696,919	476,005	2,080
TOTALS			3,222,959	2,668,167	10,400
Simple Average (Per 1,000 lbs)			309.94		
Simple Average (t)			683.33		
Life Cycle Average (Per 1,000 lbs)				256.55	
Life Cycle Average (t)				565.70	

* Assumes 10% annual inflation.

† Inflation increases the administrative overhead only.

# Assumes a 10% interest/discount rate to the beginning of the first year of operation.

** 1,000 lbs/hr x 8 hrs/day x 260 days/yr.

‡ First year costs in mid-1978 dollars - for Chicago example.

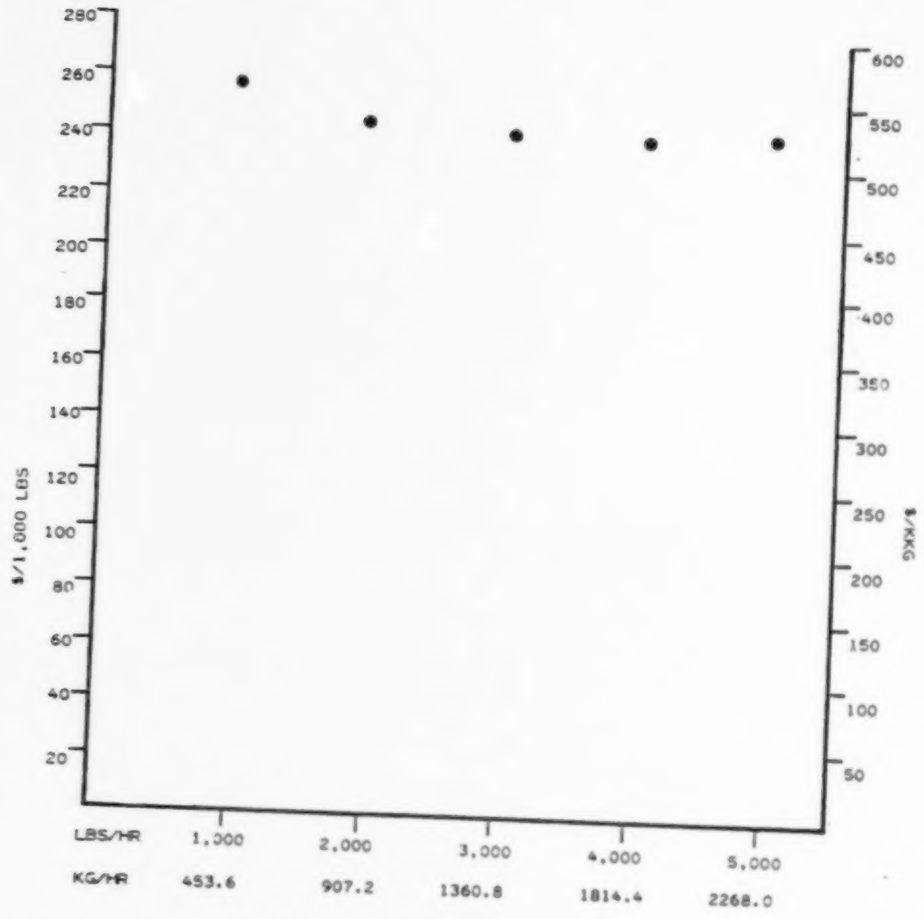

Figure 85. Incineration: life cycle costs at five scales of operation.

LAND DISPOSAL

Description

The conceptual design as shown in Figure 86 provides a basis for estimating capital and operating costs for implementing a new hazardous waste landfill. Elements for the example site are listed as follows:

- Land procurement
- Planning and design
- Clearing and grubbing
- Access roads
  - Permanent
  - Temporary
- Drainage structures
  - 30-in ½ round CMP
  - Earth walls
  - Debris basin/ea
- Fencing
- Buildings
  - Office
  - Maintenance/storage
- Utilities
  - Electric generator
  - Communications equipment
  - Water tank (10,000 gal)
- Equipment
  - Forklift
  - Front end loader
  - Track dozer
  - Pickup truck
  - Water truck
- Initial cell examination
- Hypalon liner with clay layer
- Leachate collection system
- Groundwater monitoring.

Site preparation and construction cost estimates include profit and contingencies for the contractor. The disposal cells are lined with a 30 mil synthetic liner (hypalon) having a guaranteed lifespan of 20 yrs (Figure 87). However, it is assumed that the liner may have a longer useful life, because it will not be exposed to the elements and because it will be covered with a 0.6 m (2 ft) clay layer. The estimated installed liner cost (membrane and clayey layer) is $0.44/ft^2. Three 18 m (60 ft) deep groundwater monitoring wells are specified.

Operation and maintenance costs include those costs associated with daily disposal of incoming waste and other actions required in maintaining a clean, environmentally safe,

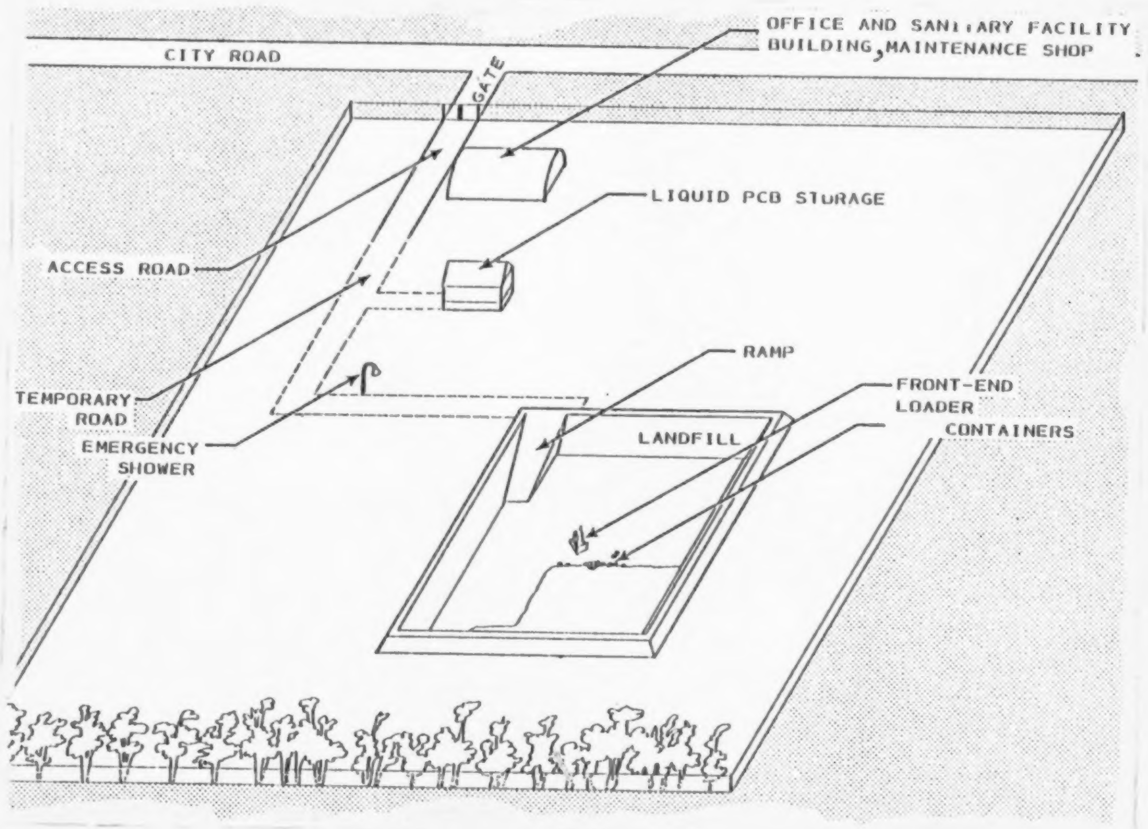
CITY ROAD
GATE
OFFICE AND SANITARY FACILITY
BUILDING, MAINTENANCE SHOP
LIQUID PCB STORAGE
ACCESS ROAD
TEMPORARY
ROAD
EMERGENCY
SHOWER
RAMP
FRONT-END
LOADER
CONTAINERS
LANDFILL

Figure 86. Hazardous waste landfill.

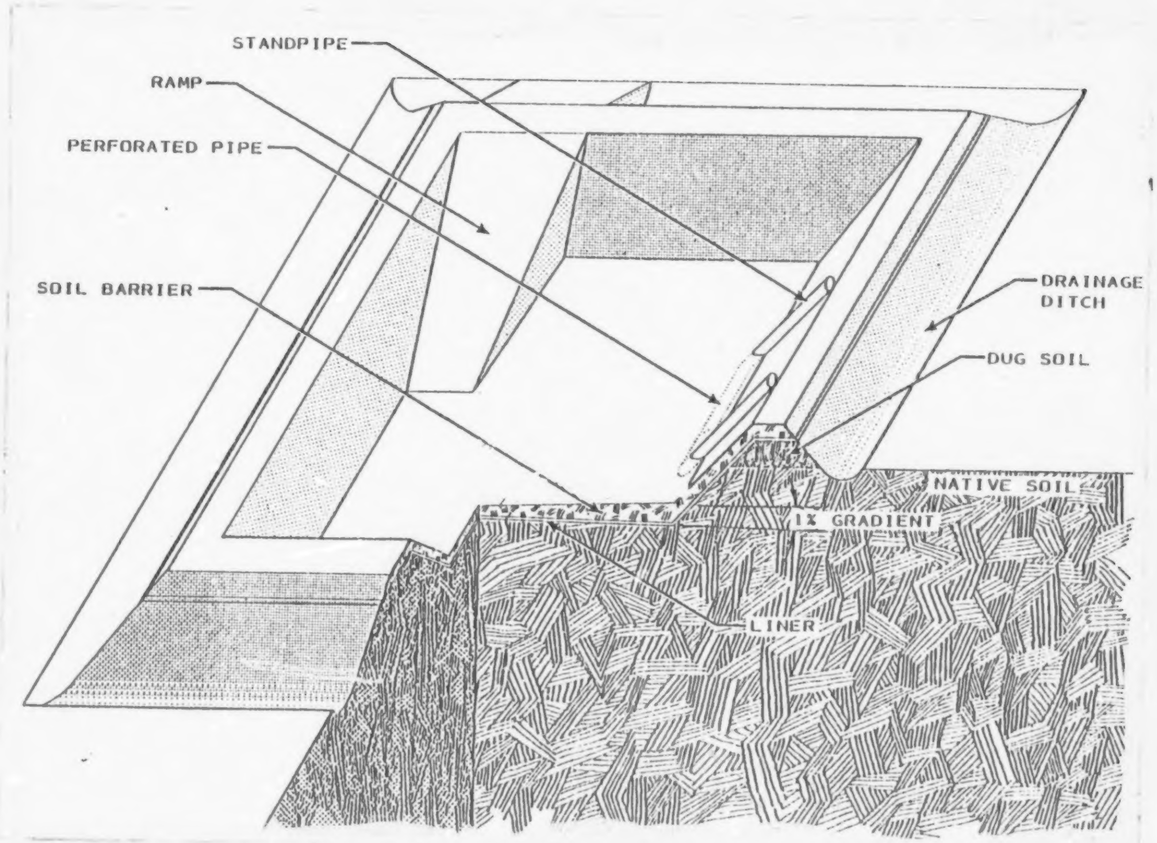
STANDPIPE
RAMP
PERFORATED PIPE
SOIL BARRIER
DRAINAGE DITCH
DUG SOIL
NATIVE SOIL
1% GRADIENT
LINER

Figure 87. Disposal cell construction.

aesthetically pleasing and efficient operation. The principal operating cost elements are personnel, equipment operating expenses (e.g., gas and oil repair), cover soil excavation and haul costs, general site maintenance (e.g., repair of drainage facilities) and administration and overhead. Costs to monitor groundwater wells are also included (27).

Note that costs to transport wastes from points of generation to the disposal site are not included here.

Changes in Configuration with Scale

Figure 88 depicts the volume requirements for other scales of operation.

Applications

The hazardous waste landfill, as described herein, may be used for ultimate disposal of any hazardous solids or residual sludges eminating from treatment facilities. Care must be taken, however, not to mix reactive wastes or create subsurface environments which may destroy the burial cell integrity. Land disposal must be used as a last resort for approved wastes which cannot be reprocessed or disposed of by other means (e.g., incinerated).

Costs

Summaries of capital and first year operating costs for land disposal are shown in Tables 64 and 65 . These estimates are based on mid-1978 costs for site preparation, structures, equipment, land, labor, utilities, etc., as applicable in Chicago, Illinois. The estimates are based on the cost files in Appendices B and C and the cost equations included in Appendix F.

As shown in Table 64 , the land disposal site, including service equipment and trucks, dozers, etc., (mechanical equipment), are costed together. The most expensive elements are the structures. These include access roads, drainage control, fencing, buildings, and the leachate collection and groundwater monitoring system. The total capital cost for the example 1,000 lb/hr facility is $2,311.135. O&M costs care minimal, the highest being for labor. The total first year operating cost for the example facility is $489,973.

Figure 89 shows the capital costs (excluding land costs) for five scales of operation and the corresponding land area requirements. The unit costs for operating a relatively small site are significantly greater than for larger sites. Such economies of scale are common for land disposal facilities.

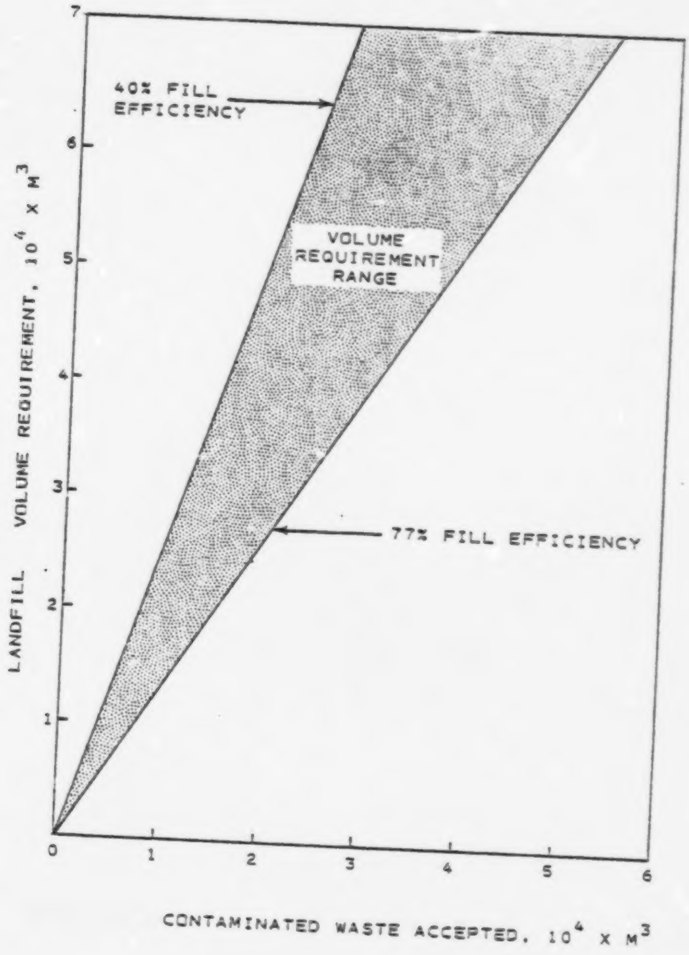

Figure 88. Volume requirements for a landfill.

TABLE 64. SUMMARY OF CAPITAL COSTS FOR LAND DISPOSAL*

Capital Cost Category Module	Costs†							Land (ft^2)
	Site Preparation	Structures	Mechanical Equipment	Electrical Equipment	Land	Other	Total	
Land disposal site	$ 121,000	$ 1,680,000	$ 230,000	$ 4,000	$ 31,100	$ 122,000	---	418,000
Total	121,000	1,680,000	230,000	4,000	31,100	122,000	---	418,000
Supplemental capital costs	---	---	---	---	---	---	---	---
Subtotal of capital costs	---	---	---	---	---	---	$ 2,188,100	---
Working capital**	---	---	---	---	---	---	13,630	---
AFDC ‡	---	---	---	---	---	---	109,405	---
Grand total of capital costs	---	---	---	---	---	---	2,311,135	---

* Scale = 1,000 lb/hr.

† Mid-1978 dollars.

** At one month of direct operating costs.

‡ Allowance for funds during construction at 5% of capital costs.

TABLE 65. SUMMARY OF FIRST YEAR O&M COSTS FOR LAND DISPOSAL*

	Costs†					
	Labor					
O&M Cost Category Module	Type 1 Operator 1 ($7.77/hr)	Type 2 Operator 2 ($9.19/hr)	Type 3 Laborer ($6.76/hr)	Energy Electrical ($0.035/KWH)	Maintenance Costs	Total
Land disposal site	$11,790	$ 69,715	$ 51,465	$ 8,300	$ 2,300	---
Total	11,790	69,715	51,465	8,300	2,300	---
Supplemental O&M costs	---	---	---	--	--	---
Subtotal of direct O&M costs	---	---	---	--	--	$ 143,570
Administrative overhead#	---	---	---	--	--	28,714
Debt service and amortization**	---	---	---	--	--	271,714
Real estate taxes and insurance‡	---	---	---	--	--	46,223
Total first year operating costs	---	---	---	--	--	489,973

*Scale 1,000 lb/hr.

† Mid-1978 dollars
# At 20% of direct operating costs.
** At 10% interest over 20 years.
‡ At 2% of total capital.

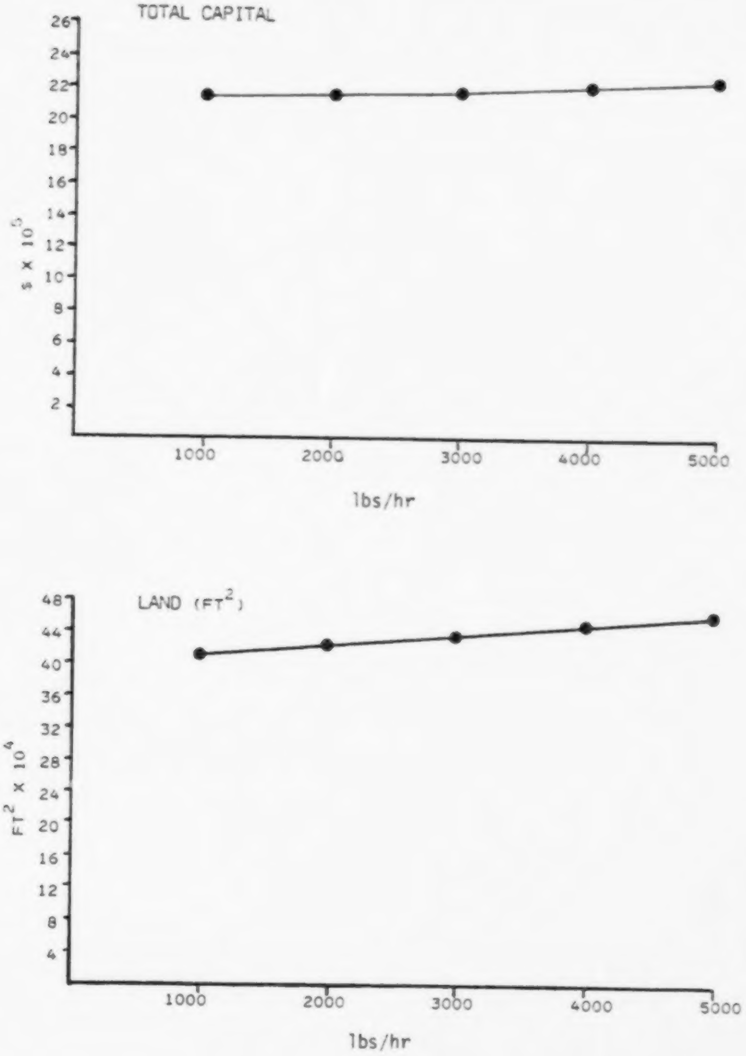

Figure 89. Land disposal: changes in total capital costs with scale.

Basic equipment items and personnel must be assigned to the site, and unused, excess capacity is available at the smaller sites. Figure 90 confirms significant economies of scale for the O&M requirements, particularly for labor and maintenance costs.

The average cost of the example 1,000 lb/hr facility, over a 20 yr life cycle, is calculated in Table 66. The life cycle average cost is $154.34/1,000 lb (340.27/t). The life cycle average cost at five scales of operation is shown in Figure 91. The significant economies of scale for both capital and annual expenditures are reflected in the average costs.

CHEMICAL FIXATION

Description

The chemical fixation process assessed herein is modeled after the portable silicate-based service offered by Chemfix, Inc. of Pittsburgh, Pennsylvania. The proprietary process (Patent No. 3,837,872) uses an inorganic chemical system which reacts with polyvalent metal ions and certain other waste components and with itself to form a chemically and mechanically stable solid. Raw waste is withdrawn from a holding lagoon into a reaction zone of a portable trailer. Once the waste is bound in the silicate matrix, it is discharged for land disposal. Leachate testing has confirmed that, after initial leaching from the freshly processed waste, the matrix resists further decomposition. Even under severe acid conditions, no metals were solubilized.

Changes in Configuration with Scale

There are no changes in configuration. The mobile units are capable of handling flow rates of 1,100 to 1,900 liters/min. If the waste has a solids content of approximately 7.5 parts per thousand, then the operational range interms is solids processed and between 489 and 783 kg/hr. However, sludges and slurries up to 50 percent solids can be handled at little extra costs. At the above flow rate, this would mean a solids handling capability of up to 57,000 kg/hr.

Applications

Chemical fixation is particularly applicable to metal wastes, such as those generated by the electroplating and metal finishing industries. The process can also be used to immobilize oily wastes and other dilute organic materials from chemical and petrochemical production. Organic compounds which cannot be handled are toxic water-soluble organics, such as pesticides, and non-water-based wastes such as solvents.

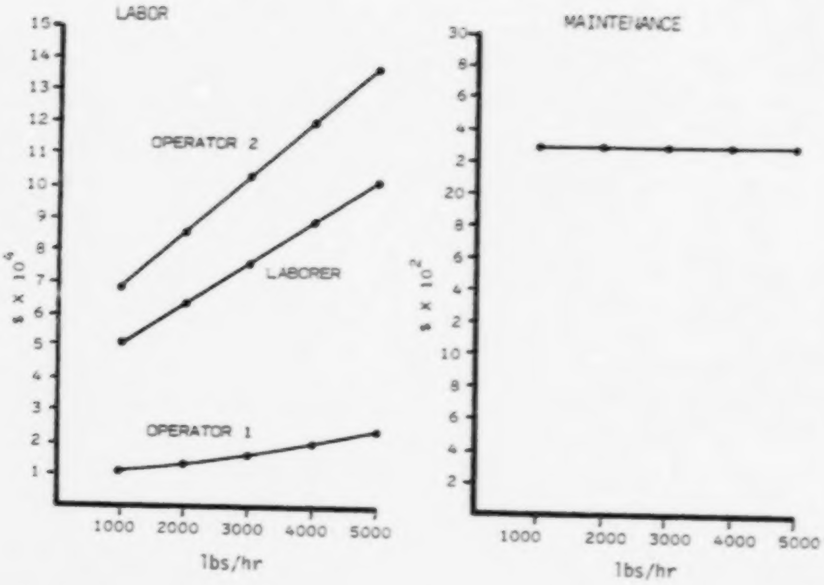

Figure 90. Land disposal: changes in O&M requirements with scale.

TABLE 66. COMPUTATION OF LIFE CYCLE AVERAGE COST FOR IMPLEMENTING LAND DISPOSAL (LIFETIME - 20 YEARS)

Item	Direct Operating Costs*	Indirect Operating Costs†	Sum Operating Costs	Present Value Annualized Costs#	Annual Quantity of Throughput (x 1,000 Lbs.)**
YEAR 1‡	143,570	346,403	489,973	489,973	2,080
YEAR 2	157,927	349,274	507,201	461,096	2,080
YEAR 3	173,720	352,433	526,153	434,813	2,080
YEAR 4	191,092	355,907	546,999	410,960	2,080
YEAR 5	210,201	359,729	569,930	389,262	2,080
YEAR 6	231,221	363,933	595,154	369,531	2,080
YEAR 7	254,343	368,558	622,901	351,628	2,080
YEAR 8	279,777	373,644	653,421	335,336	2,080
YEAR 9	307,755	379,240	686,995	320,483	2,080
YEAR 10	338,531	385,395	723,926	307,017	2,080
YEAR 11	372,384	392,166	764,550	294,734	2,080
YEAR 12	409,622	399,613	809,235	283,637	2,080
YEAR 13	450,584	407,806	858,390	273,483	2,080
YEAR 14	495,643	416,818	912,461	264,340	2,080
YEAR 15	545,207	426,730	971,937	255,911	2,080
YEAR 16	599,728	437,634	1,037,362	248,344	2,080
YEAR 17	659,700	449,629	1,109,329	241,390	2,080
YEAR 18	725,670	462,823	1,188,493	235,084	2,080
YEAR 19	798,237	477,336	1,275,573	229,476	2,080
YEAR 20	878,061	493,301	1,371,362	224,218	2,080
TOTALS			16,221,345	6,420,716	41,600
Simple Average (Per 1,000 Lbs.)			389.94 - ok		
Simple Average (t)			859.66 - 157.66		
Life Cycle Average (Per 1,000 Lbs.)				154.34 - ok	
Life Cycle Average (t)				340.27 340.21	

* Assumes 10% annual inflation.

† Inflation increases the administrative overhead only.

# Assumes a 10% interest/discount rate to the beginning of the first year of operation.

** 1,000 lbs/hr x 8 hrs/day x 260 days/yr.

‡ First year costs in mid-1978 dollars - for Chicago example.

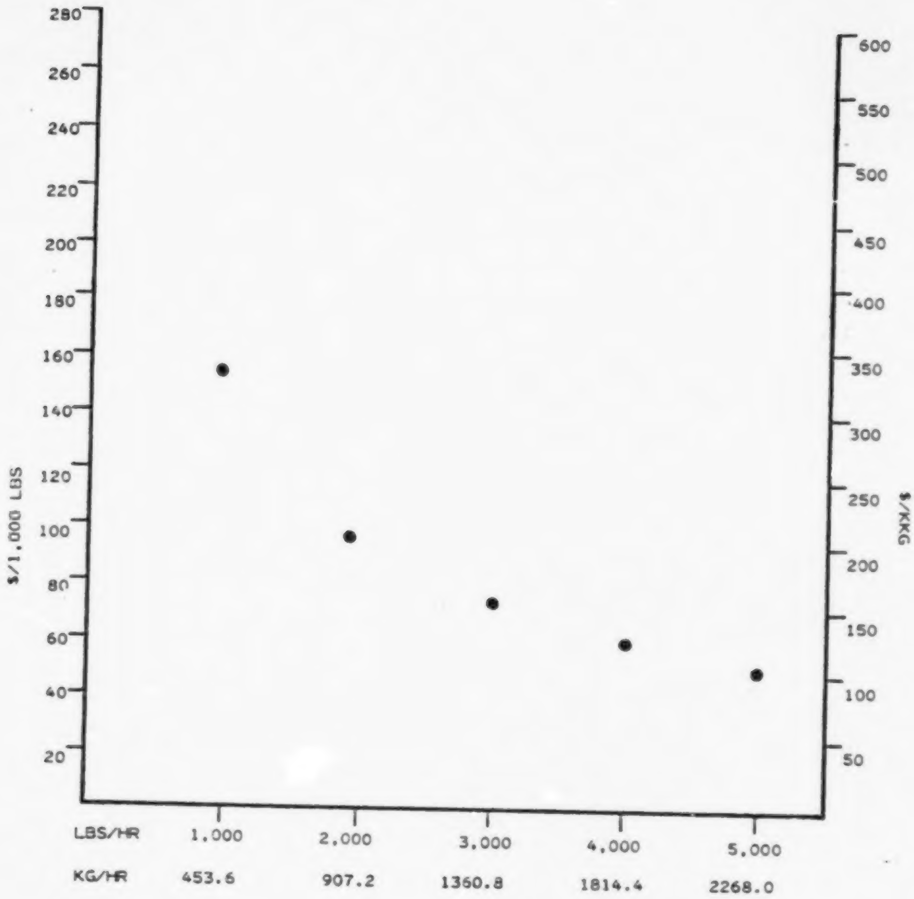

Figure 91. Land disposal: life cycle costs at five scales of operation.

Costs

Since chemical fixation is a proprietary process and only available as a service, the only cost associated with its use is that of a service charge. As listed in Appendix C, that charge is equal to $0.75/gal where solids removal is required. For wastes containing no appreciable solids, the cost is approximately $0.20/gal. Assuming a waste specific gravity of 1.0, these two operating costs at different scales of operation can be calculated. The results are shown in Figure 92. The equivalent life cycle average costs are shown in Figure 93. The life cycle average costs are calculated over a 20-year life cycle and use direct operating costs as the only input (e.g., indirect operating costs are equal to zero). The life cycle average cost at all scales of operation is equal to $546.85/1,000 lbs.

ENCAPSULATION

Description

Hazardous waste encapsulates are characterized by two elements: A stiff, weight-supporting moiety and a tough, flexible, encompassing, seam-free plastic jacket. The TRW process as developed under EPA Contract Nos. 68-03-0089 and 68-03-2037 (28) were selected as models for the cost evaluation contained here. The stiff element is geared to provide dimensional stability under mechanical stresses and compaction in the landfill. The flexible element ensures a seal, even if the stiff element is distorted and it isolates the wastes from developing leachates.

The encapsulation process, includes the following steps:

- Dewatering of wastes
- Coating the waste particulates with the resin
- Evaporating the solvent carrier
- Compacting the resin-coated particulates
- Consolidating by theremosetting to form a waste-binder block
- Encapsulating the waste-binder block (jacketing)

Resins selected for forming the waste agglomerate and the jacket are typically polybutadiene and polyethylene, respectively.

The costs for encapsulation processes are based on costs for the entire process, (e.g., single modules were not costed separately). This is due to 1) the complexity and unique nature of the unit processes, and 2) the lack of detailed cost information for certain unit processes.

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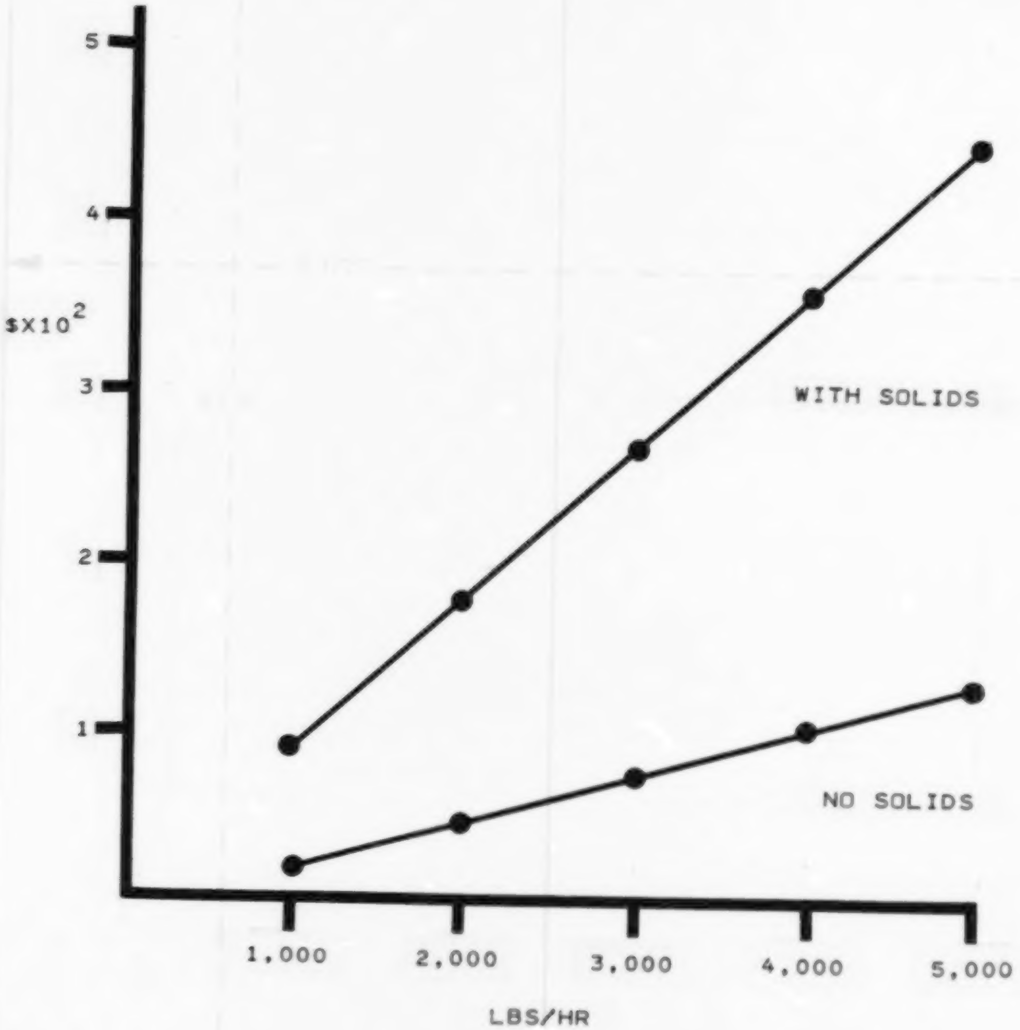

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Figure 92. Chemical fixation: two hourly operating costs at different scales of operation.

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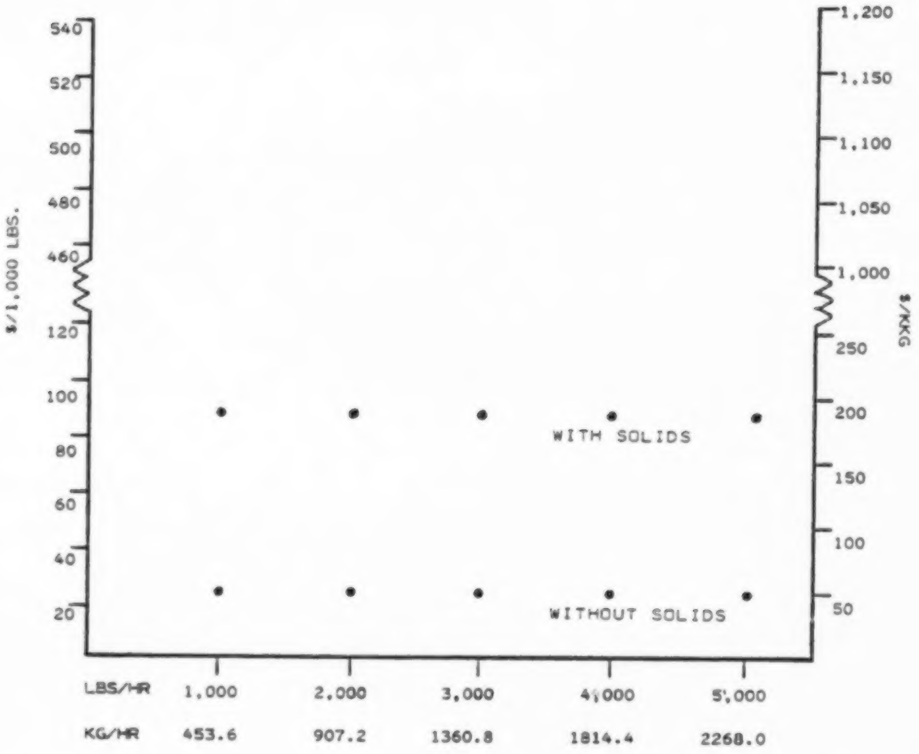

Figure 93. Chemical fixation: life cycle costs at five scales of operation.

Changes in Configuration with Scale

No large-scale encapsulation plant has been constructed yet, but it is estimated that a plant with a processing capacity of 20,000 tons/yr could be constructed utilizing the processing steps shown in Figure 94 . Larger plants would be configured with larger capacity equipment or parallel processes.

Applications

Encapsulation can be applied to any waste that has been sufficiently dewatered to make the approach cost-effective. Typical wastes include dewatered sludges from physical-chemical treatment processes. Pilot tests of encapsulation have been successfully applied to electroplating sludge (containing copper, chromium and zinc), nickel-cadmium battery production sludge (nickel and cadmium), chlorine production brine sludge, and calcium fluoride sludge(28).

Costs

Capital and first year operating costs are calculated for a phypthetical encapsulation facility (Tables 67 and 68). The main expenses are for structures and mechanical equipment. The total capital costs for the 1,000 lbs/hr facility is $300,444. The operating costs are primarily for labor (no distinction is given in the TRW estimate for different labor categories). Energy, maintenance and chemical costs are all relatively low. The total first year operating cost is $112,885.

Figure 95 shows the capital costs (excluding land costs) at two scales of operation for the technology. Cost estimates for larger scale operations were not available. The slope of the capital cost curve indicates that there is no economy of scale within the range analyzed. The capital cost is equivalent to $126.85/1,000 lbs.

Figure 96 shows the O&M requirements for the two scales of operation. Labor demonstrates economy of scale (a decrease from $16.83 to $9.62/1,000 lbs). Maintenance, energy, and chemical unit costs are consistant at both scales of operation.

The average cost of the TRW model facility over a life cycle of 7 years is calculated in Table 69 . The life cycle average cost is $46.62/1,000 lb ($102.78/t) for the 1,000 lb/hr facility. Figure 97 shows the variation in the average cost at the two scales of operation. the slight reduction in the average cost from 1,000 to 2,000 lbs/hr reflects the scale of economy noted for labor costs.

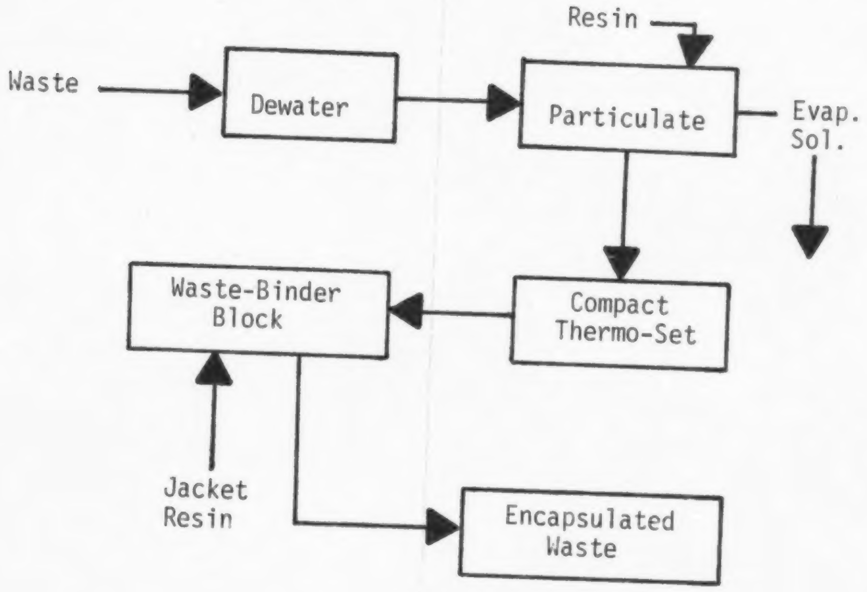
Resin
Waste
Dewater
Particulate
Evap.
Sol.
Waste-Binder
Block
Compact
Thermo-Set
Jacket
Resin
Encapsulated
Waste

Figure 94. Encapsulation: process flow diagram.

TABLE 67. SUMMARY OF CAPITAL COSTS FOR ENCAPSULATION*

Capital Cost Category Module	Costs†						Other Land (ft^2)
	Site Preparation	Structures	Mechanical Equipment	Electrical Equipment	Land	Total	
Encapsulation	$ 1,950	$ 180,000	$ 78,000	$ 3,900	$ 19,300	---	26,000
Total	1,950	180,000	78,000	3,900	19,300	---	26,000
Supplemental capital costs	---	----	----	---	----	---	----
Subtotal of capital costs	---	----	----	---	----	$ 283,150	----
Working capital**	---	----	----	---	----	3,136	----
AFDC ‡	---	----	----	---	----	14,158	----
Grand total of capital costs	---	----	----	---	----	300,444	----

* Scale = 1,000 lb/hr.

† Mid-1978 dollars.

** At one month of direct operating costs.

‡ Allowance for funds during construction at 5% of capital costs.

TABLE 68. SUMMARY OF FIRST YEAR O&M COSTS FOR ENCAPSULATION*

	Costs†							
	Labor							
O&M Cost Category Module	Type 1 Operator 1 ($7.77/hr)	Type 2 Operator 2 ($9.19/hr)	Type 3 Laborer ($6.76/hr)	Energy Electrical ($0.035/KWH)	Maintenance Costs	Chemical Costs	Total	Other Chemical (ton/yr)
Encapsulation	---	---	$ 35,000	$ 1,560	$ 780	$ 296	---	672.88
Total	---	---	35,000	1,560	780	296	---	672.88
Supplemental O&M costs	---	---	---	--	--	---	---	---
Subtotal of direct O&M costs	---	---	---	--	--	---	$ 37,637	---
Administrative overhead#	---	---	---	--	--	---	7,527	---
Debt service and amortization **	---	---	---	--	--	---	61,713	---
Real estate taxes and insurance ‡	---	---	---	--	--	---	6,009	---
Total first year operating costs	---	---	---	--	--	---	112,885	---

* Scale = 1,000 lb/hr.

† Mid-1978 dollars.

# At 20% of direct operating costs.

**At 10% interest over 7 years.

‡ At 2% of total capital.

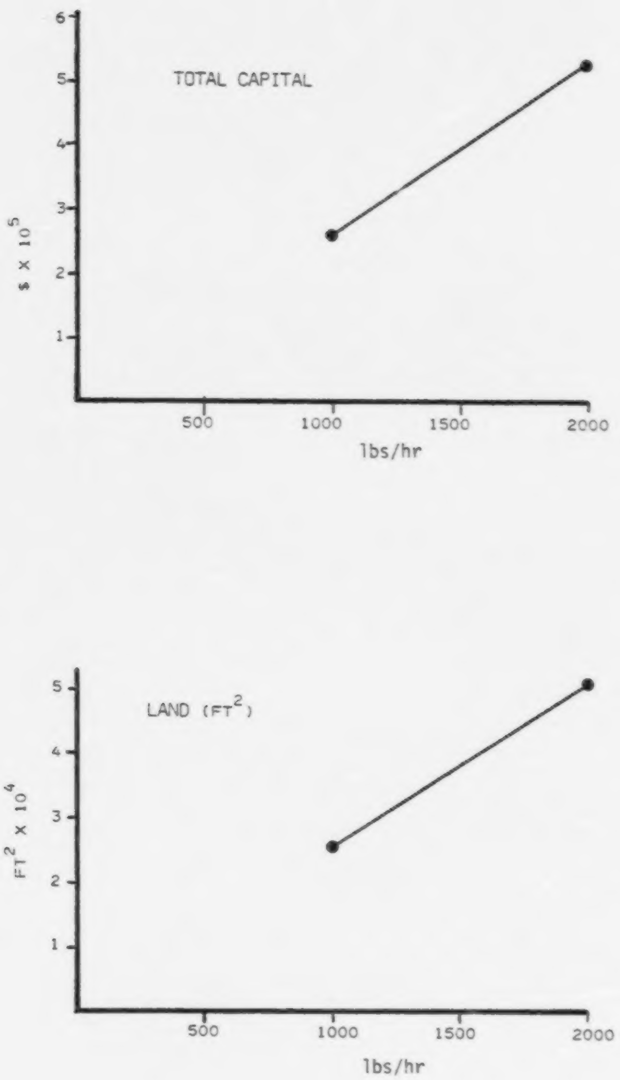

Figure 95. Encapsulation: changes in total capital costs with scale.

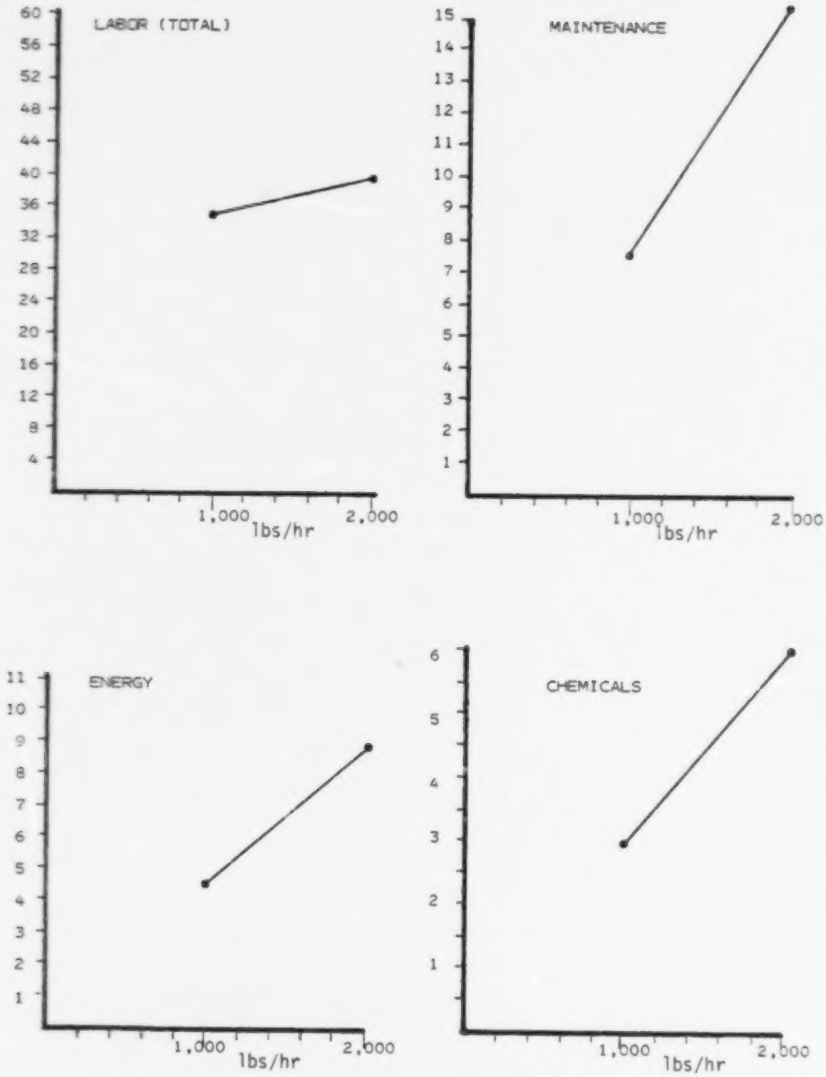

Figure 96. Encapsulation: changes in O&M requirements with scale.

TABLE 69. COMPUTATION OF LIFE CYCLE AVERAGE COST FOR IMPLEMENTING ENCAPSULATION (LIFETIME - 7 YEARS)

Item	Direct Operating Costs*	Indirect Operating Costs†	Sum Operating Costs	Present Value Annualized Costs#	Annual Quantity of Throughput (x 1,000 Lbs.)**
YEAR 1‡	37,636	75,249	112,885	112,885	2,080
YEAR 2	41,400	76,002	117,401	106,728	2,080
YEAR 3	45,540	76,830	122,369	101,132	2,080
YEAR 4	50,094	77,740	127,834	96,044	2,080
YEAR 5	55,103	78,742	133,845	91,418	2,080
YEAR 6	60,613	79,844	140,457	87,213	2,080
YEAR 7	66,674	81,057	147,731	83,390	2,080
TOTALS			902,522	678,810	14,560
Simple Average (Per 1,000 Lbs.)			61.91		
Simple Average (t)			136.66		
Life Cycle Average (Per 1,000 Lbs.)				46.62	
Life Cycle Average (t)				102.78	

---

* Assumes 10% annual inflation.

† Inflation increases the administrative overhead only.

# Assumes a 10% interest/discount rate to the beginning of the first year of operation.

** 1,000 lbs/hr x 8 hrs/day x 260 days/yr.

‡ First year costs in mid-1978 dollars - for Chicago example.

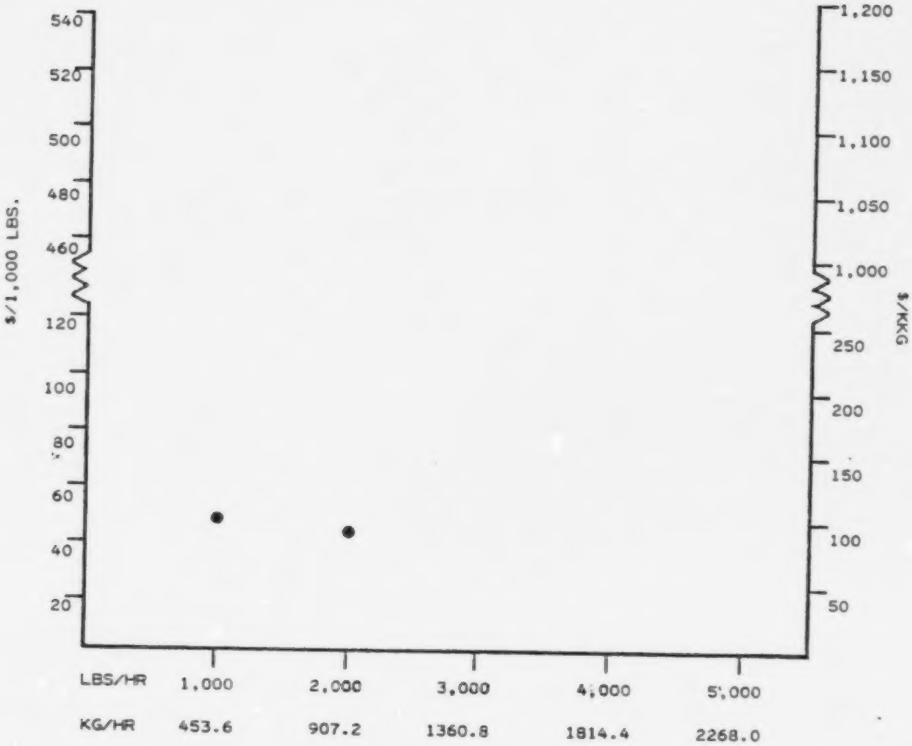

Figure 97. Encapsulation: life cycle costs at two scales of operation.

SECTION 7

ASSESSMENT OF RISKS

The objective of this section is to assist the user in identifying potential risks associated with the existence and operation of each treatment and disposal technology. To this purpose, the following risk categories have been defined and assessed in a qualitative manner:

- Catastrophic events
- Unexpected downtime
- Unexpected equipment damage
- Adverse environmental impacts.

The discussions and comparisons included in this section are designed to help the user further assess the desirability of a particular treatment/disposal scheme. The risk assessment is typically secondary to the cost-effectiveness analyses presented earlier.

Risk analysis is at best a semi-quantitative process. The approach taken here is similar to that presented by EPA for resource recovery projects (29). Resource recovery risks are similar to those in hazardous waste management in the following respects:

- The technologies represent different levels of development (e.g., pilot versus full-scale)

- The technologies process varying wastestreams and produce varying byproducts for further processing

- Equipment and operations must be carefully controlled to avoid breakdown, inefficient operation, or undesirable environmental conditions

- The technologies are, to varying degrees, susceptible to catastrophic events.

Primary differences between the two types of technologies include the design of unit processes, and the emphasis on production and marketing of certain recovered products.

In the following discussions and comparisons, the risks associated with capital equipment and operations are emphasized and issues of financial risk, risk management, input withdrawals, competition and construction risks are minimized. The intent is to characterize only those risks that are directly related to the level of complexity of typical installations, or that stem from or have direct impacts on typical equipment and plant operation.

CATASTROPHIC EVENTS

Major catastrophies are unforeseeable occurrences that can destroy structures and equipment installations. As a category of risk considered here, they include earthquakes, floods, tornados, and fires. Such events involve the risk of losing part or all of the capital investment. The probability of such loss can differ appreciably among technologies. Lagoon systems, for example, have few associated structures or equipment that can be destroyed by such disasters. A complex distillation or carbon adsorption system, on the other hand, would probably be severly damaged by an earthquake or tornado.

Certain areas of the United States may be prone to certain types of catastrophies. The Gulf Coast, for example, experiences tornados and hurricanes. Heavily forested areas may become involved in fire and destroy adjacent structures. Earthquakes are also specific to certain geographical areas.

The probability of the occurrence of a catastrophy is entirely independent of the presence and type of technology. But the impact of a catastrophic event depends on the technology type and is roughly equal to the total value less site preparation and land. Loss of service also represents real costs to waste generators, who must seek alternative treatment/disposal arrangements. However, since the costs for this are difficult to quantify and vary greatly, they will not be estimated here. Catastrophic events that destroy onsite treatment/disposal facilities may also destroy or interrupt the source of wastes.

Table 70 includes qualitative ratings of the probability of severe damage (at least 50% loss of capital) resulting from each type of catastrophy. It is important to distinguish between the probabilities presented in Table 71 and the probability of catastrophic occurrences which are independent of the type of technology.

Earthquakes

Typically, seismic loadings on structures or vessels are caused by horizontal ground motions that transmit forces into structures and equipment. Towers or scaffolding with high centers of gravity and rigid connections to the ground can be severly damaged or completely toppled by failure of near-ground supports. The hydrodynamic masses for liquid-filled rigid tanks excited by horizontal translational impulses may also result in structural damage and possible release of contents to the environment (30, 31). The impact on low lying concrete or metallic structures may be less severe, but there is still potential for slab and wall fractures or equipment

TABLE 70. RISK OF DAMAGE FROM CATASTROPHIC EVENTS FOR HAZARDOUS WASTE TREATMENT/DISPOSAL TECHNOLOGIES*

	Earthquake		Floods				Tornados			Fire			
Technology	Toppled Structure	Fracture	Transloc	Immersion	Deposition	Erosion	Transloc	Vortex	Impingment	Elec. eq. damage	Direct Combustion	Melting	Explosion
Precipitation/ flocculation/ sedimentation	-	+	-	-	+	+	-	-	-	-	-	-	-
Filtration	-	+	-	+	+	+	-	-	-	-	-	-	-
Evaporation	+	+	+	+	-	+	+	-	+	-	+	-	+
Distillation	+	+	+	+	-	+	+	+	+	-	+	-	+
Flotation	-	+	+	-	-	+	+	-	-	-	+	-	-
R.O./ultrafiltration	-	+	+	+	-	-	+	-	-	+	+	+	-
Oxidation/reduction	-	+	+	+	-	-	+	-	-	-	+	-	+
Hydrolysis	-	+	+	+	-	-	+	-	-	-	+	-	+
Aerated lagoon	-	-	-	-	+	+	-	-	-	-	-	-	-
Trickling filter	-	+	-	-	-	+	-	-	-	-	-	-	-
Waste stabilization pond	-	-	-	-	+	+	-	-	-	-	-	-	-
Anaerobic digestion	-	+	+	-	-	+	-	-	-	-	-	-	+
Carbon adsorption	+	+	+	+	-	-	+	+	+	+	+	+	-
Activated sludge	-	+	+	-	+	+	-	-	+	+	-	-	-
Incineration	+	+	+	+	-	-	+	+	+	+	+	+	-
Land disposal	-	-	-	-	+	+	-	-	-	-	-	-	-
Chemical fixation	+	+	+	+	-	-	+	-	+	+	+	+	-
Encapsulation	+	+	+	+	-	-	+	-	+	+	+	+	-
Evaporation pond	-	-	-	-	+	+	-	-	-	-	-	-	-

* + = impact.

- = no or minimal impact.

TABLE 71. POTENTIAL ENVIRONMENTAL RISKS ASSOCIATED WITH HAZARDOUS WASTE TREATMENT/DISPOSAL ALTERNATIVES

	Type of Environmental Impact				
Technology	Potential for Health Impacts	Potential for Surface Water Pollution	Potential for Sub-surface Pollution	Potential for Air Emissions	Ash/Sludge/ Concentrate Production
Precipitation/ flocculation/ sedimentation	0	+	-	-	+
Filtration	0	+	-	-	+
Evaporation	0	0	-	+	+
Distillation	0	0	-	+	+
Flotation	0	+	-	0	+
Reverse osmosis	0	-	-	-	+
Ultrafiltration	0	-	-	-	+
Chemical oxidation/ reduction	0	+	-	-	0
Hydrolysis	0	0	-	-	0
Aerated lagoon	+	+	+	+	-
Trickling filter	+	+	0	+	+
Waste stabilization pond	+	+	+	+	-
Anaerobic digestion	0	0	0	0	+
Activated sludge	0	+	0	0	+
Carbon adsorption	0	+	-	-	0
Incineration	+	-	-	+	+
Land disposal	+	+	+	+	-
Chemical fixation	-	-	0	-	-
Encapsulation	-	-	0	-	-
Evaporation pond	+	+	+	+	+

+ = possible impact.
0 = variable.
- = no possible impact.

misalignment, even under moderate seismic occurrences. Like other types of catastrophies, the probability of severe earthquake is related to geographical location (Figure 98).

Floods

Floods can damage treatment and disposal installations by one or several means:

- Translocation (sweeping away by flowing water)
- Immersion (water damage to equipment and electrical service)
- Deposition (substantial deposits of sand or silt by flood waters)
- Erosion (soil erosion and undermining of footings, foundations, or dikes).

Each of these processes is analyzed individually in Table 70 . The flood potential for the mean annual and 10-year flood locations in the United States is shown in Figure 99 .

Tornados/High Winds

The direct impact of tornados is to uproot structures and equipment. The probability of damage is therefore related to the number of free-standing, tall structures included in the technology equipment. Under high wind conditions, strong vortexes can form around objects placed in the wind (32). Such vortexes create momentary areas of low pressure, which in the case of tall, free standing towers, can enhance vibrational frequencies and result in structural damage. High winds impinging on fixed structures (e.g. buildings) can also have damaging impacts through direct contact or generation of negative pressures on the leeward side of the structures. Each technology is therefore assessed (Table 70) for its likelihood of sustaining damage to tall, free-standing towers or stacks (vortex), moderately sized fixed structures (impingement), and low-profiled structures and equipment (translocation). States having the highest threat of tornados are Illinois and Florida (Figures 100, 101 and 102). Figures 103 and 104 show geographical distribution of thunderstorms and high winds.

Fires

The susceptibility of a plant to damage by external fire (e.g., not originating in or caused by plant operation) is a function of the flammable or heat-sensitive equipment and structures included therein. Concrete basins, for example, would not be as susceptible as an ultrafiltration unit or a tank containing chlorine gas under pressure The types of heat/fire damage assessed (Table 70) include:

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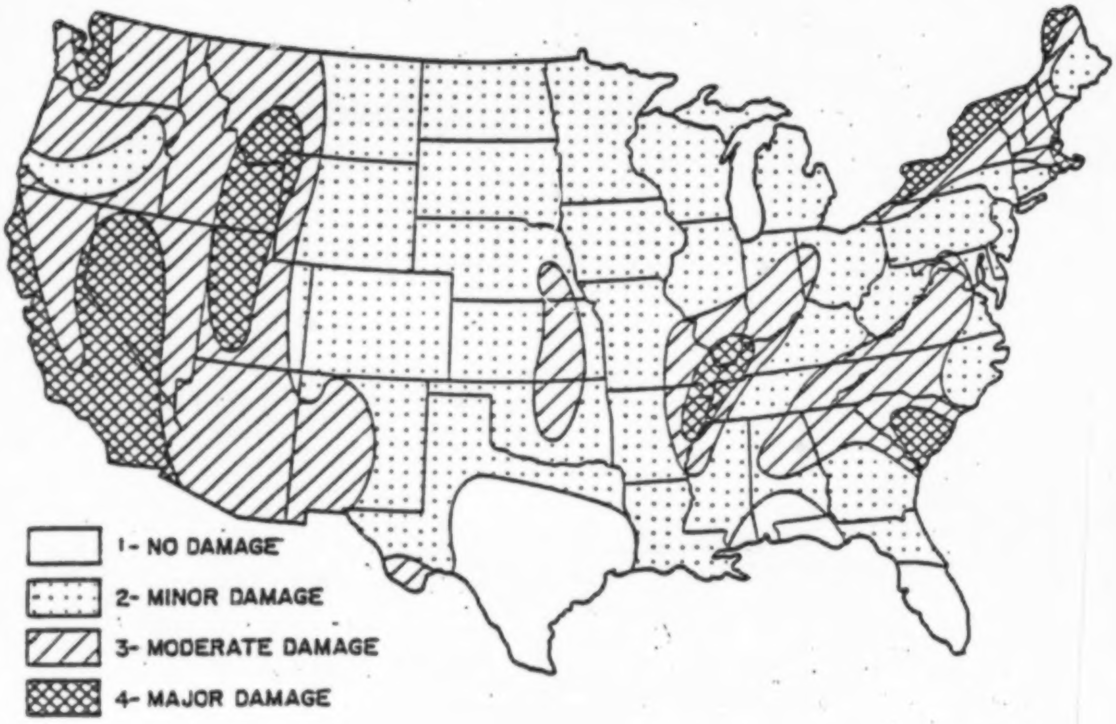
1- NO DAMAGE
2- MINOR DAMAGE
3- MODERATE DAMAGE
4- MAJOR DAMAGE

Figure 98. Potential earthquake damage levels for various areas of the United States, 1979.

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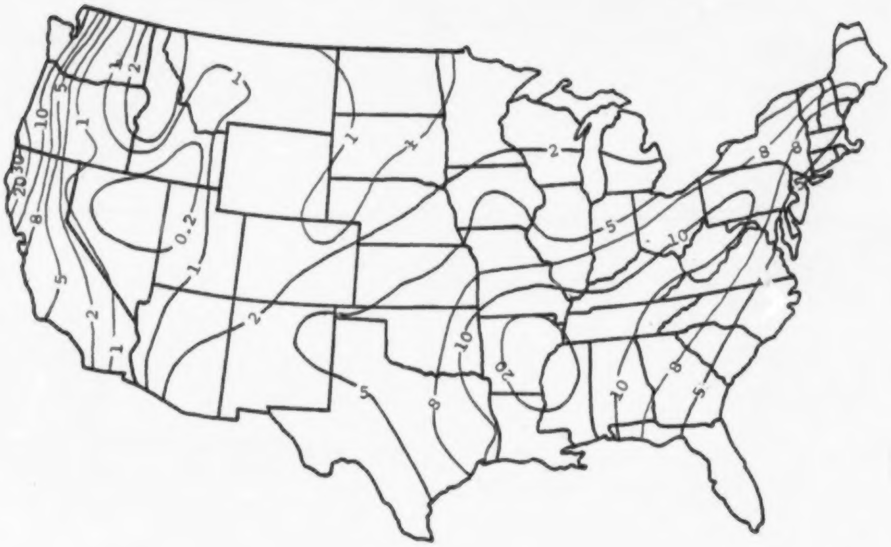
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Mean annual flood, 1965
(Thousands of cubic feet per second.)

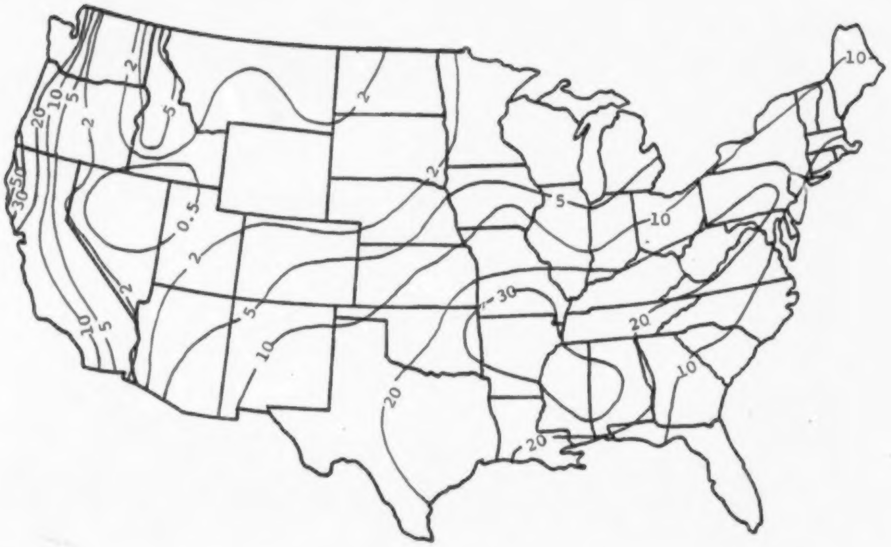
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Figure 99. Flood potential for the mean annual and ten year floods in various United States locations.

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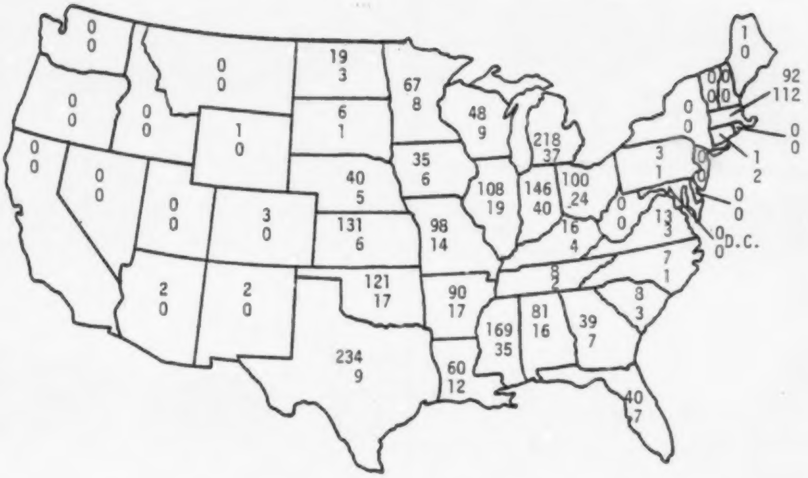
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131 6
98 14
108 19
146 40
100 24
0 0
16 4
3 1
0 0
13 3
1 0
0 0
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92 112
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1 2
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0 0 D.C.
7 1
8 2
8 3
2 0
2 0
121 17
90 17
234 9
60 12
169 35
81 16
39 7
40 7

Figure 100. Deaths from tornados, 1953. (Upper figure is number of deaths, lower figure is number of deaths per 10,000 square miles.)

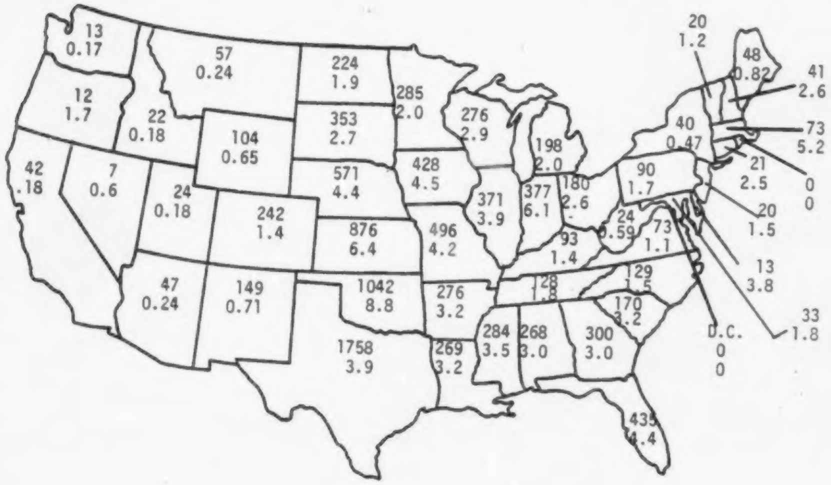
13 0.17
12 1.7
22 0.18
57 0.24
224 1.9
353 2.7
285 2.0
276 2.9
198 2.0
42 .18
7 0.6
24 0.18
104 0.65
571 4.4
428 4.5
371 3.9
377 6.1
180 2.6
90 1.7
40 0.47
20 1.2
48 0.82
41 2.6
73 5.2
21 2.5
0 0
20 1.5
13 3.8
33 1.8
D.C. 0 0
242 1.4
876 6.4
496 4.2
93 1.4
24 0.59
73 1.1
129 1.5
128 1.8
170 3.2
47 0.24
149 0.71
1042 8.8
276 3.2
1758 3.9
269 3.2
284 3.5
268 3.0
300 3.0
435 4.4

Figure 101. Tornado incidence by State and area, 1953. (Upper figure is number of tornados, lower figure is mean annual number.)

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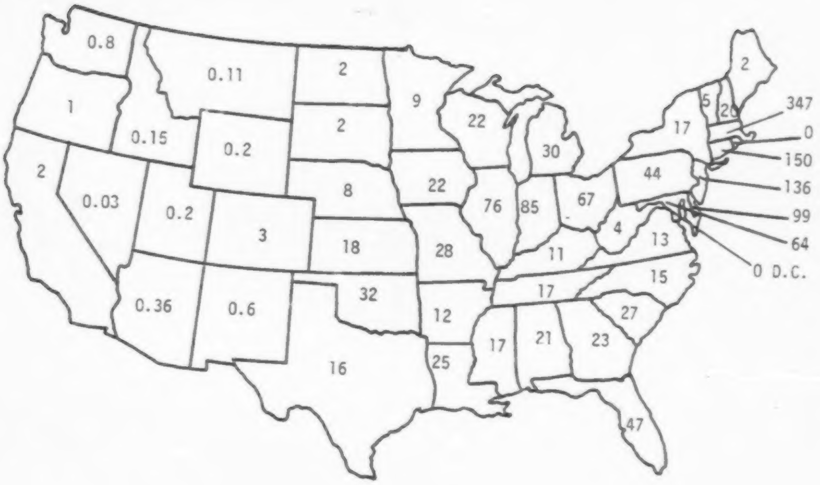
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Figure 102. Threat rating from tornados, 1953.
(10 = 10 tornados per 10,000 square miles and 10 people per square mile or 1 tornado per 10,000 square miles and 100 people per square mile.)

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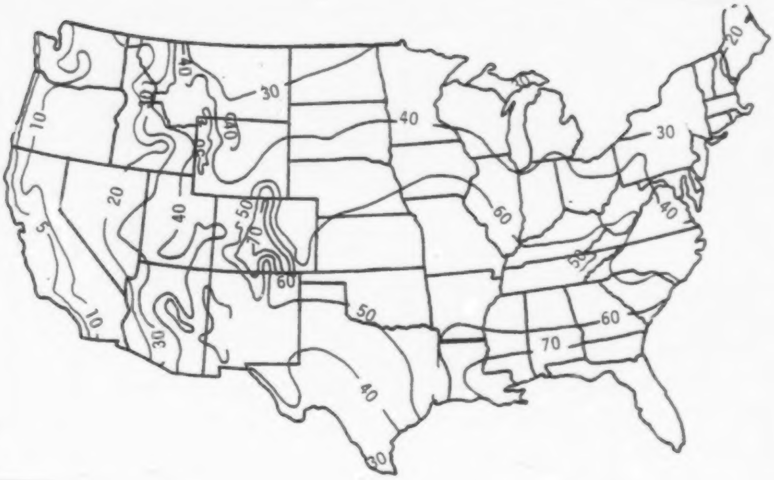
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Figure 103. Mean annual number of days without thunderstorms, based on data through 1964.

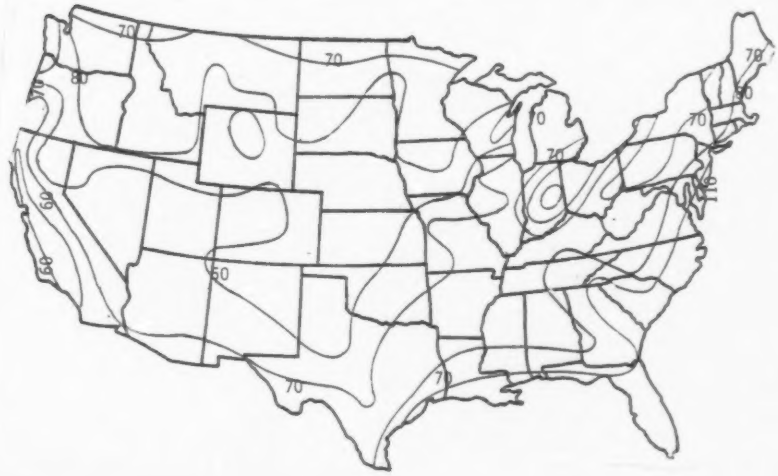
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Figure 104. Maximum expected winds: 50 year mean recurrence interval. (Based on data through 1968.)

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- Electrical equipment damage
- Direct combustion of structures/equipment
- Melting of hoses, metallic pipes, etc.
- Heat or fire induced explosion (gases under pressure, chemical reactions, etc.).

For purposes of the risk assessment presented in Table 70, it was assumed that all unit processes were equally exposed to flammable surroundings (i.e., the possibility of being housed in fire-protected structures was ignored).

UNEXPECTED DOWNTIME

Unlike catastrophies, disruption in plant operations has numerous possible causes including unexpected waste characteristics, system reliability, chemical supply/labor disruptions, and other factors. Some causes (such as chemical or labor supply) are independent of the type of technology, although their potential impact is not. Other causes, such as system reliability, are inherent to the type of technology.

The following possible causes of system disruption are considered:

- System reliability/complexity
- Stability (sensitivity to wastestream fluctuations)
- Labor productivity
- Energy dependence
- Sophistication of maintenance requirements
- Water dependence
- Chemical dependence
- Amenability to upgrading.

Unexpected equipment damage is treated separately in the following section. Stability is assessed in Table 72 according to fluctuations in waste flow rates and constituent concentrations. There are cases where facilities have been forced to shut down because of violations of discharge limitations. This assessment therefore includes an indication of the amenability of various technologies to upgrading or retrofitting with additional treatment equipment.

TABLE 72. RISK OF UNEXPECTED DOWNTIME FOR HAZARDOUS WASTE TREATMENT/DISPOSAL TECHNOLOGIES*

	Cause of System Disruption								
Technology	Reliability/ Complexity	Flow Stability	Waste Concentration	Labor	Energy	Maintenance	Chemicals	Water Supply	Upgrading
Precipitation/flocculation/sedimentation	-	-	-	+	+	-	+	+	-
Filtration	o	-	-	+	-	-	-	+	-
Evaporation	+	+	-	+	-	+	-	-	+
Distillation	+	+	-	+	-	+	-	-	+
R. O./ultrafiltration	+	+	+	-	+	+	+	+	o
Oxidation/reduction	o	-	-	-	-	-	+	-	o
Hydrolysis	o	-	-	-	-	-	+	-	o
Aerated lagoon	o	-	+	-	+	-	o	-	-
Trickling filter	o	+	+	+	-	-	o	-	-
Waste stabilization pond	-	-	+	-	-	-	o	-	+
Anaerobic digestion	o	-	+	+	-	-	-	-	+
Carbon adsorption	+	-	-	-	+	+	-	+	+
Activated sludge	o	+	+	+	+	+	o	-	-
Incineration	+	+	-	+	-	+	-	-	-
Land disposal	-	-	-	+	-	-	+	-	+
Chemical fixation	+	+	-	-	+	+	+	-	+
Encapsulation	+	+	-	-	+	+	+	-	o
Evaporation pond	-	-	-	-	-	-	-	-	o
Flotation	o	-	-	-	+	-	+	-	-

* + = high impact.
o = overuse impact.
- = no or minimal impact.

UNEXPECTED EQUIPMENT DAMAGE

Risks in this category include the cost of damage sustained over and above any associated downtime costs (see preceeding section) and expected equipment maintenance. Both non-technology-related and technology-related causes are possible, with a number of resulting impacts. The risk of equipment damage is directly related to the reliability and complexity of the technology. This risk assessment is included in Figure 105.

ADVERSE ENVIRONMENTAL IMPACTS

Socio-legal restrictions for hazardous waste treatment/disposal processes have been extensively defined by RCRA.

Specific restrictions apply to the following types of environmental impacts:

- Exposure of operating personnel and adjacent public (health effects)
- Contamination of surface water resources (water pollution)
- Contamination of subsurface resources (groundwater pollution)
- Improper sludge handling
- Discharge of hazardous combustion products to the air (air pollution).

Typically, these environmental factors constitute the weak link in risk analysis because it is difficult to assign costs to them as they relate to various sites. The ramifications of discharges are not always related to the technology, but rather to independent environmental factors. The variety of possible impacts is difficult to predict and further confounds an evaluation that is not site specific. There are, however, some environmental risks associated with treatment/disposal technologies that may be qualitatively compared. Table 71 summarizes these factors. Note, however, that where treatment/disposal alternatives for a specific project site are being compared, site-specific weighing schemes should be used.

Regulations may be implemented that require unforeseen capital expenses because of significant changes in design or additional discharge treatment (upgrading).

As shown in Table 71, certain treatment/disposal technologies have greater potential for environmental pollution than others. Typically, the regulations are aimed at reducing or eliminating such contamination. Reverse osmosis and ultrafiltration have high-purity aqueous discharges and would

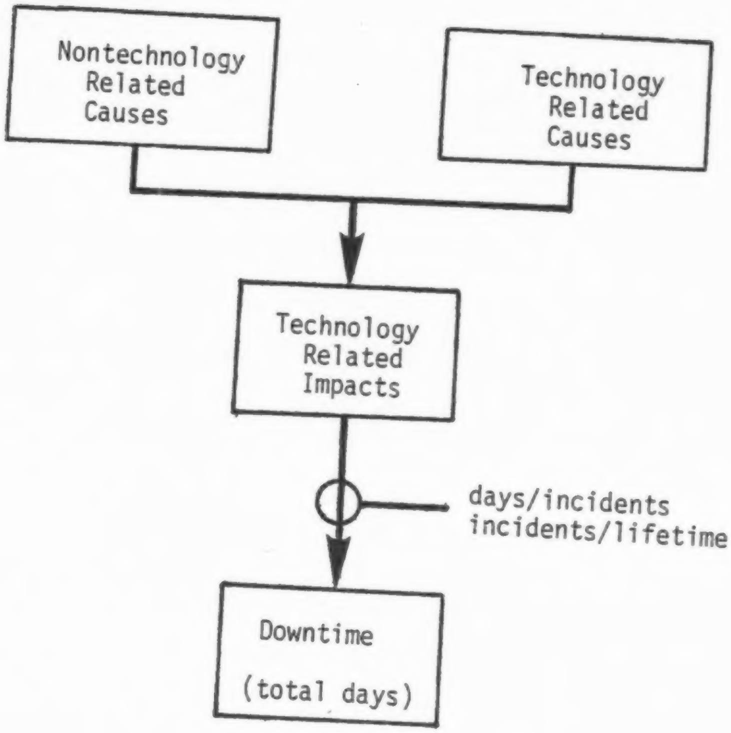
Nontechnology Related Causes
Technology Related Causes
Technology Related Impacts
days/incidents
incidents/lifetime
Downtime
(total days)

Figure 105. Process for assessing equipment damage risk.

probably not require further processing. They do, however, produce hazardous concentrates that are subject to controlled handling and subsequent disposal. Lagoons and land disposal technologies may pose a threat to subsurface water resources. Liners or leachate collection systems mandated by law will place additional financial burdens on existing facilities.

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(For complete literature citations, see bibliography numbers in parentheses)

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13 Neptune Microfloc Corvallis, Oregon
14 Cleaver Brooks Milwaukee, Wisconsin
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20 Greaves Company Seattle, Washington
21 Pfaulder Company Rochester, New York
22 FMC Corporation Pleasantville, California
23 Inland Transportation Company Seattle, Washington
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